A FEASIBILITY STUDY OF SOLVENT-ASSISTED GRAVITY DRAINAGE OF HEAVY OIL USING PROPANE VAPOUR: DEVELOPMENT OF THE VAPEX PROCESS

by

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FINAL REPORT

by

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1. ABSTRACT

This final report summarizes experimental work carried out during the investigation of solvent-assisted gravity drainage (SOLAGD) of heavy oils using solvent vapour. The experiments were conducted in a scaled visual Hele-Shaw cell and, later on, in a scaled packed cell with Tangleflags North heavy oil and propane. Common to all phases of the experimental development, the process involves the contacting of bitumen with propane vapour at or above its dew point in a vertical cell. In the initial experiments, the Hele-Shaw cell was exposed to saturated propane vapour along a vertical edge which was left open and the oil drainage rate was determined from photographs.

In later experiments, saturated propane vapour entered the vertical Hele-Shaw cell at the top and formed a characteristically V-shaped chamber. The rate of oil drainage was studied as a function of saturation temperature (and therefore, pressure) at a constant rate of withdrawal. The initial oil production rate increased with temperature until it tapered off near the critical temperature for propane.

In the final experiments, a scaled packed cell with seven thermocouples arranged in a '7-spot pattern' was designed. All heat to the oil was supplied by simultaneous injection of propane and hot water. The production increased immediately after the introduction of propane at the end of the hot water cycle and the recoveries were encouragingly high. Based on these positive results, a new vapour extraction (VAPEX) process is being developed.

2. INTRODUCTION

There are extensive deposits of heavy oils in Saskatchewan and Alberta which can only be recovered with a low recovery efficiency by conventional methods. Primary recovery in the best of these heavy oil reservoirs can yield about 6 percent of the original oil in place. Water flooding can improve the recovery but only to an extent of 1-2 percent because of the adverse mobility ratio.

Thermal recovery processes using steam can be effective but these are uneconomic in many of the 'Lloydminster-type' reservoirs because the deposits are relatively thin and heat loses to the over and underburden are excessive.

One potential means for overcoming the problem of heat loss is to use solvents. Rather than lowering the viscosity of the oil by heating, dilution with a solvent is used instead. In a recent paper [6] we have shown that the recovery mechanism using solvents is very similar to that found with steam. Whereas with steam it is necessary for heat to diffuse into the reservoir by thermal conduction, the process with solvents involves molecular diffusion. The rates at which the processes occur can be described by analogous equations[1]:

$$Q = 2\sqrt{2kg\phi\Delta S_o HN} \quad , \quad m^3 m^{-1} d^{-1} \tag{2.1}$$

where N is a dimensionless number defined for the steam process as

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[1]The equations in this section are dimensionally consistent. Thus, for example, if Eq.(2.1) is to yield Q in m^3 per m of horizontal well per day, then k should be in m^2, g in m/d^2 and H in m.

$$N = \int_{T_{min}}^{T_s} \frac{\alpha \Delta\rho}{\mu} \cdot \frac{dT}{(T - T_R)} \qquad (2.2)$$

In this equation dimensionally consistent units should be used, eg.

α = thermal diffusivity, $m^2 d^{-1}$

$\Delta\rho = \rho_{bit} - \rho_{steam}$, kg m^{-3}

T = temperature, ^oC, and

μ = viscosity at T, kg $m^{-1} d^{-1}$

For the solvent process, N is defined as

$$N = \int_{c_{s_{min}}}^{1} \frac{D_s(1-c_s)\Delta\rho}{\mu} \cdot \frac{dc_s}{c_s} \qquad (2.3)$$

where D_s = intrinsic solvent diffusivity, $m^2\ d^{-1}$

$\Delta\rho = \rho_{soln} - \rho_{solv}$, kg m^{-3}

c_s = solvent concentration, vol. fraction

μ = solution viscosity, kg $m^{-1} d^{-1}$

The rate at which the liquid solvent process occurs is disappointingly slow. The reasons for this become clear from a comparison of Eqs (2.2) and (2.3): The molecular diffusivity is smaller than thermal diffusivity and the potential gradient effecting flow is less because of the smaller density difference.

An attractive idea for reducing these obstacles is to use a solvent which is introduced in the vapour form. If such a process is carried out at reservoir temperature, the volume formerly occupied by the displaced oil is left filled with low density solvent vapour, a considerable fraction of which can be recovered later by pressure blow-down, and there are no heat losses involved.

However, the preliminary experimental work using a Hele-Shaw cell which is reported here shows that, if this process were performed at the reservoir temperature then, although the rate of oil production would be much higher than that with liquid solvents, it would still be lower than that required for an economic operation. However, it is also shown by these experiments that if the reservoir temperature could be raised to only 40-50^{o}C, then the process would proceed at a faster rate; heat losses would still be vastly lower than those for conventional steam recoveries.

The work reported later in the report develops the idea of using warm vapourized solvents further. The reservoir is warmed by hot water injected simultaneously with propane vapour. This results in a laterally spreading vapour-filled chamber that replaces the drained oil.

The advantage of using a vapour instead of a liquid lies in obtaining larger density differences to accelerate the removal of diluted oil by gravity drainage. The solution drains, driven by gravity, to a well placed low in the formation. This idea is attractive if the production well is a long horizontal one so that the contact with the reservoir can be improved.

3. PRELIMINARY EXPERIMENTS

3.1 Development of Apparatus with Line Source Cell.

The initial experiments were designed to measure the rate of oil recovery from a vertical Hele-Shaw cell immersed in an atmosphere of saturated propane at equilibrium temperature (Fig.3.1.1). The propane vapour was allowed to contact the oil along a vertical edge of the cell (line source) and the diluted oil drained from the same exposed edge (Fig.3.1.2). As the leaching proceeded, some precipitated asphaltenes were left behind (see Fig.3.2.1). The Hele-Shaw cell was placed in a pressure vessel with two windows, one for photographing the progress of the bitumen drainage, the other for back illumination of the cell. The pressure vessel was, in turn, immersed in an oil bath which kept the whole process at a constant temperature. The body of the pressure vessel was made of 6061-T6 aluminium alloy and the windows of 1 inch thick and 4 inches in diameter Tempo glass. The pressure vessel was tested to 1550 psig with water at room temperature. It could be used safely for pressures ranging from 0 to 500 psig and temperatures up to 95°C. Most operating conditions were, however, in the 100 to 300 psig range and 20-70°C, as the liquid propane inside the pressure vessel established an equilibrium with its vapour for each pre-set bath temperature. The small volume of oil from the Hele-shaw cell (typically 0.62 ml) then drained to the bottom of the pressure vessel. Schematic drawings of the apparatus and of the Hele-Shaw cell are given in Figures 3.1.1, 3.1.2 and 3.1.3.

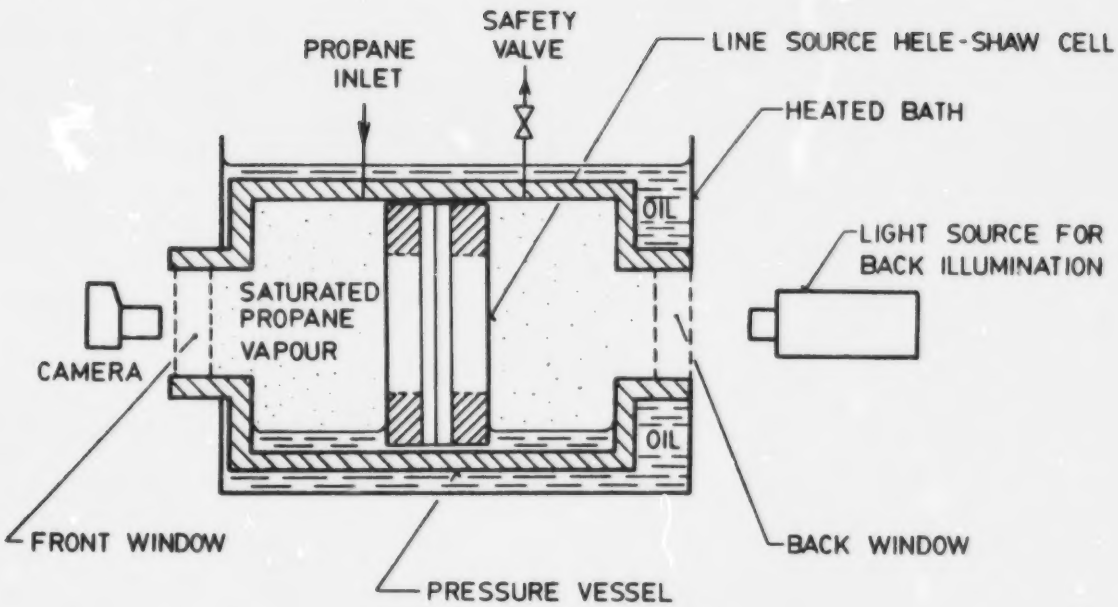

FIGURE 3.1.1: A Schematic Diagram of the Experimental Set-up for a Line Source Hele-Shaw Cell

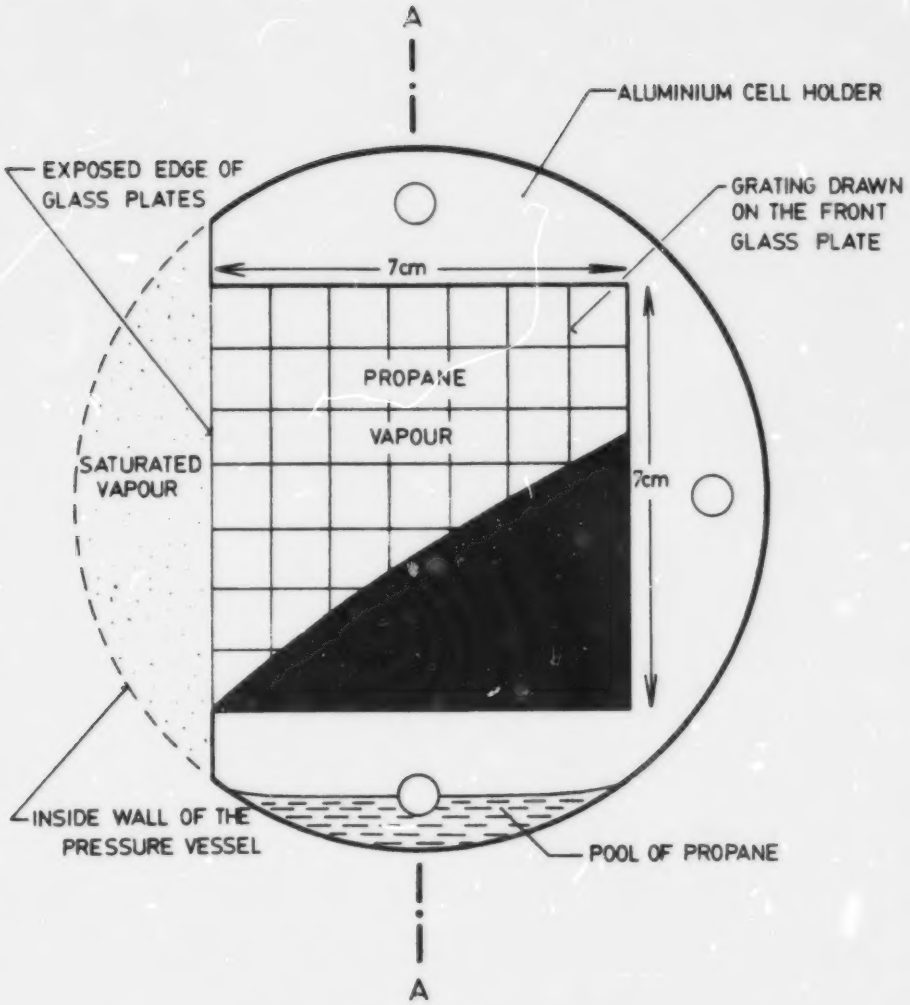

FIGURE 3.1.2: Line Source Hele-Shaw Cell (front view)

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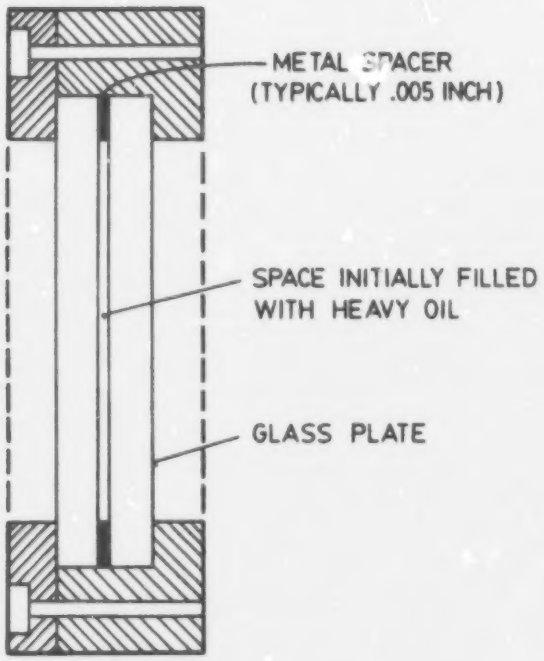

A

FIGURE 3.1.3: Cross-Sectional Drawing of the Line Source Hele-Shaw Cell (side view)

3.2 Results and Discussion of Preliminary Experiments

Figure 3.2.1 contains photographs of a preliminary experiment with Lloydminster crude. This heavy oil contains approximately 12 percent of asphaltenes [7]. The photographs show that the propane vapour mixes readily with the light fractions of the oil, leaving behind some asphaltenes as an immobile precipitate adhering to the glass. It was observed that the drainage occurs in a number of single steps, and that the asphaltenes precipitate out in a number of parallel ribbons, making a record of the drainage process on the cell walls. It is important to realize that in the process of precipitation of the heavy asphaltenes the remaining oil becomes less viscous and therefore drains more easily.

The precipitation and subsequent behaviour of asphaltene particles should be investigated carefully. It is quite possible that clogging of narrow pore throats of a porous media could occur, causing blockages and impairment to the oil flow. This effect should be avoided. One potential way to control the precipitation might be to mix the propane with a non-condensable gas such as nitrogen. This could lower the partial pressure, and therefore the concentration, of propane below that required for the precipitation. This idea was not followed further in this work because there seemed to be little difficulty caused by the precipitation.

In our experiments with the Hele-Shaw cell a severe blockage and impairment of flow due to asphaltenes precipitation has not been observed; the precipitated asphaltenes adhered to the glass walls. However, as reported in Section 3.3.7, the tendency towards blockage increased at lower temperatures. Danesh et al. [5] found that miscible displacement of light oil (35.3°API with 2 % wt asphaltenes) with

propane did not result in significant precipitation of asphaltenes within the pores. However, if the propane was mixed with crude oil and pumped into the reservoir model, then pore blockage due to asphaltene deposition and build-up was observed in their experiments.

Photographs of a preliminary run showing the Propane–Lloydminster Crude interface with time. Notice the precipitated asphaltenes.

Interface at 315 minutes, line source Hele–Shaw cell.

Interface at 375 minutes in the line source Hele–Shaw cell.

FIGURE 3.2.1

3.3 Improvements of the Experimental Set-up: Point Source Cell

3.3.1 Hele-Shaw Cell

After the initial experiments several design changes were made to the Hele-Shaw cell and to the apparatus. The line source cell used in the initial work had one whole edge exposed to the propane and represented one half of a spreading solvent chamber as it would be created in a reservoir around a vertical injection well located above a horizontal producer. The new Hele-Shaw cell was a point source type with propane injection at a point near the top and with production near the bottom. A schematic drawing of this cell is given in Figure 3.3.1.1. It represents a vertical cross-section through a reservoir having two horizontal wells drilled through it, i.e., the injection well near the top and the producer at the bottom. After the initial communication has been established, the solvent chamber (which is filled with propane vapour) spreads sideways, displacing the original oil.

3.3.2 Back Filling of the Mounted Hele-Shaw Cell

It was found cumbersome and time consuming to dismantle the pressure vessel and remove the HelerShaw cell for cleaning after each experimental run. To overcome this, a backfilling facility was developed which enabled the operator to fill the cell while it was mounted in the pressure vessel. A schematic drawing of this arrangement is given in Figure 3.3.2.1.

The production line was closed and nitrogen pressure that was higher than the equilibrium vapour pressure inside the pressure vessel was applied to oil in an oil cylinder. This resulted in oil flowing back into the Hele-Shaw cell against the vapour pressure of propane. The progress of the cell re-filling could be observed by viewing the

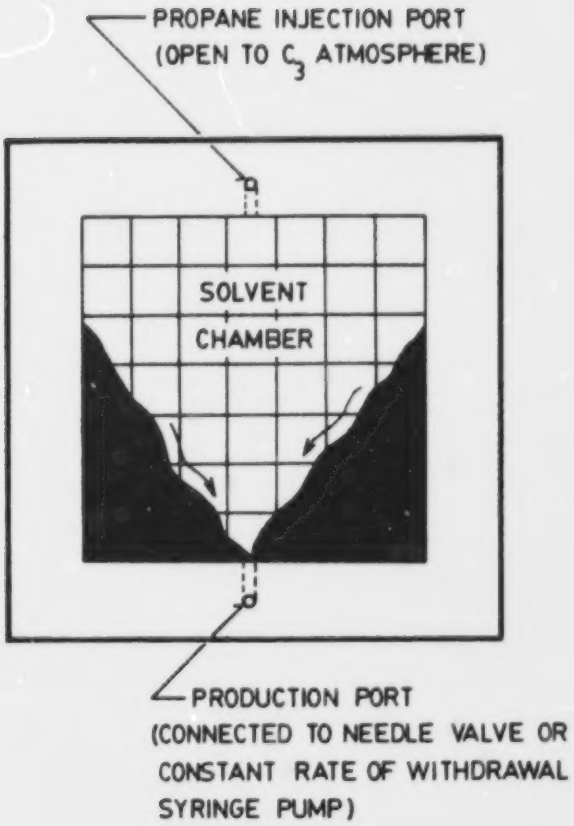

FIGURE 3.3.1.1: **Schematic Representation of the Point Source Hele-Shaw Cell. Typical Spacing is .005 inch. Grid Lines are 1 cm Apart. Solvent chamber is filled with propane vapour.**

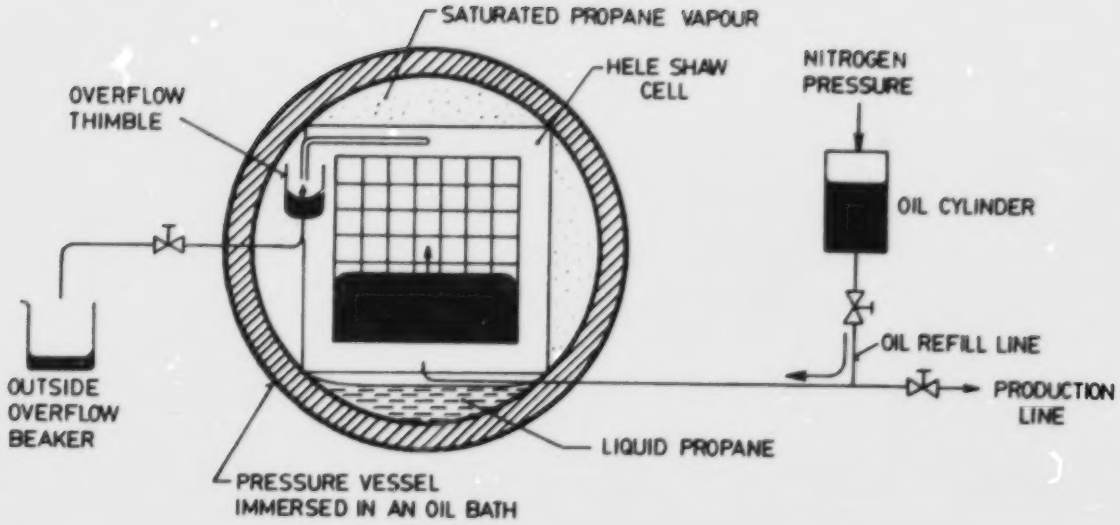

FIGURE 3.3.2.1: A Diagram of a Back-filling Arrangement for a Mounted Hele-Shaw Cell

rising oil interface through the pressure vessel front window. The excess oil passed via a 1/16" OD tubing into an overflow thimble which could be emptied into an outside beaker whenever required. At the end of a re-fill, the oil refill line would be shut, the production line opened and the propane vapour would enter the top of the Hele-Shaw cell through the 1/16 OD stainless steel tubing (small dead volume). This was the time zero for the experiment.

3.3.3 Regulation of Back Pressure and the Rate of Withdrawal

Depending on the equilibrium temperature as determined by the oil bath, the pressure within the Hele-Shaw cell during an experiment was typically between 100 and 500 psi. Such a high pressure required a means for regulating the production flow from the cell to prevent excessive amounts of propane vapour from passing freely through the cell. In the initial approach, a fine metering valve was inserted into the line to throttle the outflowing fluids. However, this arrangement proved unsatisfactory, mostly due to the fact that the valve could not adequately regulate a 2-phase flow passing through it. As a result, sudden pressure variation within the vessel would occur and the vapour-liquid equilibrium would be upset. The solution to this problem was found in the installation of a backpressure, constant withdrawal syringe-type ISCO pump into the production line. For this purpose, the pump was modified internally and several electrical connections were changed. During an experiment, the pump plunger withdrew total product at a pre-set constant rate and the vapour-liquid equilibrium inside the pressure vessel was therefore not affected.

The effect of the withdrawal rate on the oil production was tested up to a rate of 25 ml/hr. It was determined that beyond a certain value

of the withdrawal rate, there was no gain in the oil production (i.e. only more propane was passed unnecessarily through the Hele-Shaw cell)[2]. The rate of removal of the products was therefore set at 5 ml/hr and all the experiments in the point source HelerShaw cell were carried out at this setting. In most of the experiments this withdrawal rate results in some bypass of propane vapour.

A proper technique for setting up the back pressure at the start of the experiment was critical in achieving an early breakthrough along the centerline of the cell. This involved initial pressurization of the pump with nitrogen just below the anticipated equilibrium pressure of the propane. For instance, if the pressure vessel temperature was to be 63°C, with an anticipated equilibrium vapour pressure of 300 psi, then the pump would be pressurized with nitrogen to about 295 psi, the pressure vessel filled with liquid propane, the pump back pressure quickly readjusted to 1-2 psi below the actual vessel pressure, and the connecting valve between the ISCO back pressure pump and the pressure vessel opened. In this way the propane breakthrough in the cell would occur 2-3 minutes after the start of the experiment in accordance with the controlled constant rate of withdrawal of 5 ml/hr.

3.3.4 Evaluation of Production Rates

The oil production rates from the HelerShaw cell were evaluated from photographs taken during the course of each experiment. The solvent areas on the photographs correspond to the produced oil and they were determined as a function of time using a planimeter or a digitizing

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[2]A similar phenomenon is observed in our Steam-Assisted Gravity Drainage experiments where excess production of steam results in little additional oil.

pad. The areas in arbitrary planimeter units (APU) were then converted to cm^2 using the centimeter grid drawn on the front glass plate of the Hele-Shaw cell as a reference. There were typically 8-12 photographs taken during an experiment. Since the rate of production diminishes with the square root of height [6], the initial rates of oil production were used to compare runs for different equilibrium temperatures (cf. Sec. 3.3.8).

3.3.5 Scaling Conditions for Time and Permeability

Two scaling conditions were used for determining the cell permeability required for the scaled visual model experiments and to predict the field time.

The first scaling condition is obtained by considering the bitumen drainage flow in the reservoir (see List of Symbols), i.e.

$$Q_b = \frac{V\phi\Delta S_o}{t} = \frac{k}{\mu} \cdot \frac{dP}{dH} \cdot A \qquad (3.3.5.1)$$

Dividing through by the area and replacing the hydrostatic pressue gradient by ρg we obtain,

$$\frac{H\phi\Delta S_o}{t} = \frac{k}{\mu} \rho g \qquad (3.3.5.2)$$

where H is the reservoir (or cell) height.

Rearranging and using the definition of kinematic viscosity,

$$kgt = H\phi\Delta S_o \nu \qquad (3.3.5.3)$$

$$\text{or} \qquad \left(\frac{kt}{\phi\Delta S_o H}\right)_M = \left(\frac{kt}{\phi\Delta S_o H}\right)_F \qquad (3.3.5.4)$$

where M = model and F = field. The acceleration due to gravity and the kinematic viscosity cancel out in Eq.(3.3.5.4).

The second scaling condition is obtained from the dimensionless ratio Dt/H^2, i.e.

$$\left[\frac{\phi t}{H^2}\right]_M = \left[\frac{\phi t}{H^2}\right]_F \qquad (3.3.5.5)$$

where the diffusivity cancels out and the porosity makes some allowance for the diminished reservoir diffusivity resulting from the volume occupied by the rock pores. Eliminating t_F/t_M from Eqs. (3.3.5.4) and (3.3.5.5), we obtain

$$k_M = k_F \cdot \frac{H_F \phi_M^2 (\Delta S_o)_M}{H_M \phi_F^2 (\Delta S_o)_F} \qquad (3.3.5.6)$$

where, for the HelerShaw cell [8], $k_M = \frac{b^2}{12}$, $\phi_M = 1$ and $(\Delta S_o)_M = S_{oi} - S_{or} = 1$.

Assuming the following values for the field and our model,

$H_M = .07$ m $\qquad\qquad$ $\phi_F = .35$

$H_F = 10$ m $\qquad\qquad$ $(\Delta S_o)_F = .86$

$k_F = 1$ darcy

then the cell permeability, k_M, is 1356 darcy. This leads to $b = 5.0 \cdot 10^{-3}$ inch or 127 μm. From Eq. (3.3.5.5) it also follows that

1 model hour = 6.66 years in the field (3.3.5.7)

The glass plate spacing in the point source Hete-Shaw cell was therefore set at 5 thousandths of an inch.

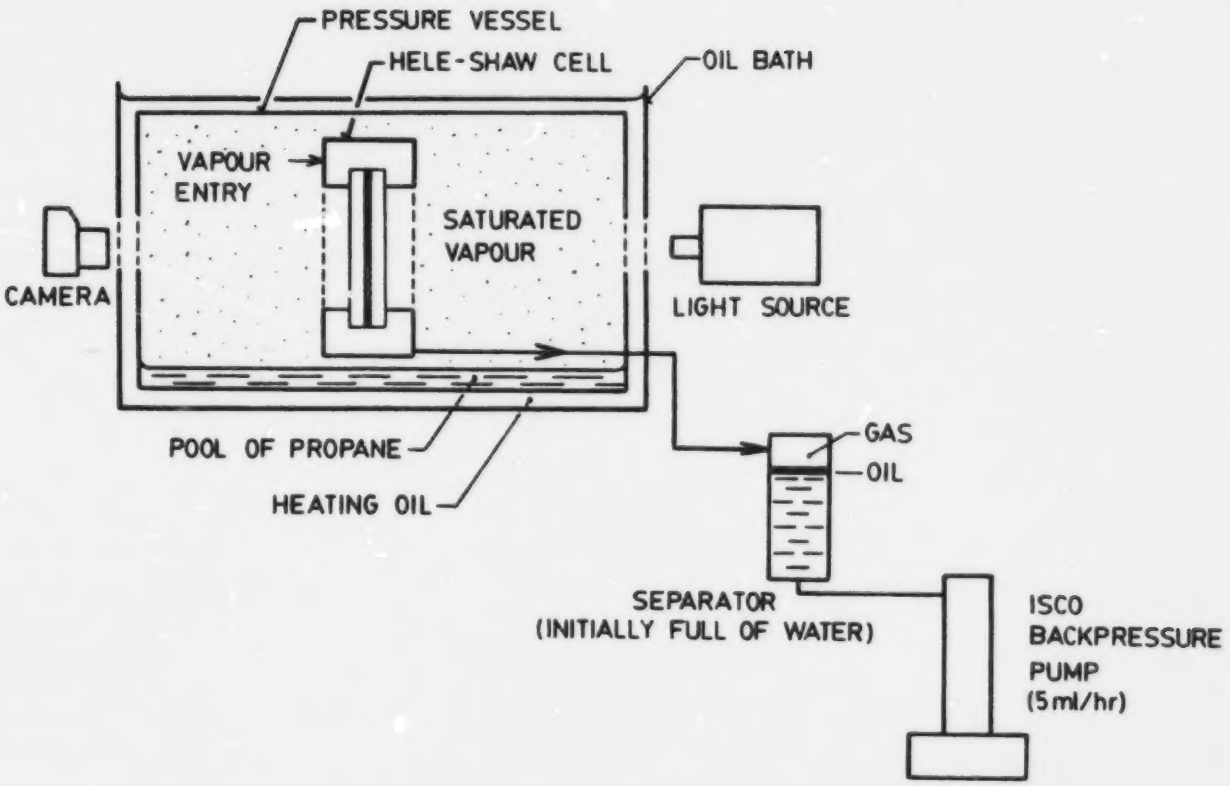


FIGURE 3.3.6.1: Experimental Set-up for a Point Source Hele-Shaw Cell With a Constant Rate of Withdrawal Syringe-Type ISCO Pump.

3.3.6 Experimental Results Obtained With the Point Source HelerShaw Cell

The objective of this part of the work was to determine the effect of higher propane pressure (and hence temperature) on the production drainage rate from the point source Hele-Shaw cell with a permeability of 1356 darcies (i.e. with plate spacing b = .005 inch). The cell was filled with Tangleflags North heavy oil (see Figs A2 and A4 in Appendix A) and immersed in an atmosphere of saturated propane vapour at equilibrium temperatures ranging from 20°C to 90°C. The schematic drawing of the apparatus is given in Figure 3.3.6.1. Photographs taken during the run were evaluated to determine the initial drainage rate for a given cell temperature.

The results are listed in the following table and plotted in Figure 3.3.6.2. Table 3.3.6.2 contains the oil density as a function of temperature.

TABLE 3.3.6.1. RESULTS OF EXPERIMENTAL RUNS

Cell Equilibrium Temperatures (°C)	Initial Drainage Rate (mℓ/hr)
20	0.18
32	0.34
39	0.47
46	0.99
50	1.05
50	1.23
55	1.40
59	2.00
60	1.85
70	2.51
75	2.72
80	2.98
90	3.27
90	3.33

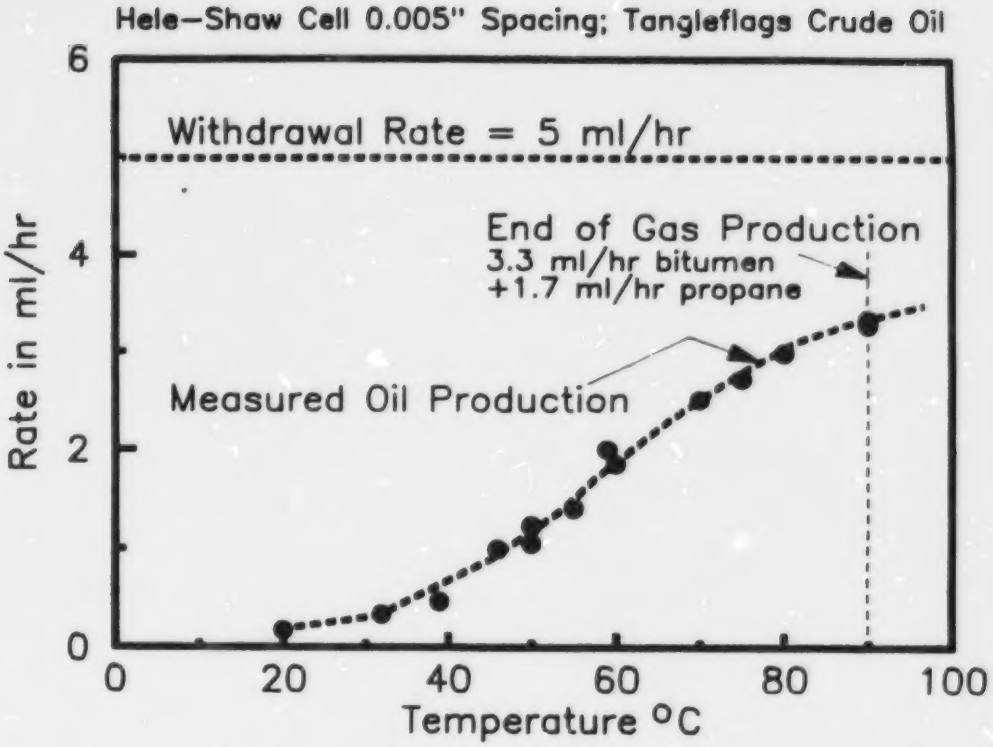


FIGURE 3.3.6.2: Effect of Temperature on Heavy Oil Leaching with Propane Vapour

TABLE 3.3.6.2. Density of Tangleflags North Heavy Oil as a Function of Temperature.

T, °C	ρ, g/cm^3
19.5	0.9719
26.5	0.9710
44.0	0.9656
54.0	0.9591
60.0	0.9552
75.0	0.9461
90.0	0.9383

As may be seen from Figure 3.3.6.2, the gravity drainage production rate of oil from the Hele-Shaw cell increased with temperature up to about 90°C, where the rate began to level off progressively. Also

in Figure 3.3.6.2 is a broken line which corresponds to the **total** (vapour plus liquid) withdrawal rate as set by the pump. Thus, as the oil production rate increased from 0.18 mℓ/hr to 3.33 mℓ/hr, the propane (liquid plus vapour) leaving with the product decreased from 4.82 to 1.67 mℓ/hr. At the low temperatures, the produced propane volume was almost entirely the excess vapour. At the high temperatures, the produced propane was essentially all dissolved in the produced oil.

It appears then that the dissolved propane was of the order of 1.7 mℓ per 3.3 mℓ of oil, i.e. about 0.5 Bbl/Bbl. It is realized that the propane requirements are a critical characteristic of the process and direct measurements of the propane consumption were made in the next series of experiments. However, for the present, it can be concluded that the propane consumption is probably not excessively high.

The measured rates are encouraging, particularly at the high temperatures. Above 60°C, the cell drained in less than an hour and, according to our previous calculations, this would correspond to less than 6.6 years for a reservoir 10 m thick containing 1 darcy sand. In the next version of the process which is described later, temperatures above ambient have been used and practical production drainage rates have been achieved.

Although no error bars are indicated in Figure 3.3.6.2, the reproducibility of experimental measurements was satisfactory. It may be seen from the initial rate measurements presented in Table 3.3.6.1 (eg. at 50, 59/60 and 90°C) that the rates vary from 2 to 15% for repeat tests at a given temperature. Such variation is to be expected in view of the fact that the whole procedure is very sensitive to the way the pressure vessel is purged prior to the start and to the initial pressure

differential established between the backpressure pump and the cell. Both of these factors tend to affect the initial drainage rate. Since drainage rates decrease with the square root of the hydrostatic head of the draining fluid in the cell [6], it is the initial rates that are compared and plotted in Figure 3.3.6.2.

3.3.7 Experimental Photographs

Three sets of eight photographs each of the Hele-Shaw cell leaching experiments are presented in this report to demonstrate the rate evaluation procedure and to show the drainage mechanism (Figs. 3.3.7.1, 3.3.7.2 and 3.3.7.3).

Each photograph is a close-up view of the glass plates of the vertical Hele-Shaw cell (initially full of Tangleflags North heavy oil) which is illuminated by a light source from the back (see Fig.3.3.6.1). The window area is 7 x 7 cm as indicated by a graticule drawn on the glass. The cell rested in an atmosphere of saturated propane vapour above a shallow pool of liquid propane at the bottom of the pressure vessel. The pressure vessel was in turn immersed in a constant temperature oil bath and the whole system was allowed to reach an equilibrium before the start of the experiment. The propane vapour was introduced at the top centre between the glass plates and the mobile oil was drained at the bottom centre. The total rate of drainage was 5 mℓ/hr, as determined by withdrawal of the ISCO back pressure pump; the plate separation was 0.005 inches. The three sets of 8 photographs each are for temperatures of 20, 55 and 90°C, and the relevant data are listed in Tables 3.3.8.1, 3.3.8.2 and 3.3.8.3.

Photograph 1/20°C (Fig.3.3.7.1) shows clearly the initial breakthrough channel at 8 minutes after the start. One may also notice the formation of incipient side channels and the boundary layer flow alongside the channel walls. During this part of the process, the oil is pushed by the propane. However, the rate of withdrawal is controlled so that a maximum of only 5 mℓ/hr of propane vapour can bypass.

Photographs 2 to 5/20°C (Fig.3.3.7.1) show the formation of a characteristic V-shaped drainage channel. This V-channel is initially narrow (about 45°) but eventually opens to a full 180° (see photo 8/20°C). Each photograph contains a frozen-in record of the drainage history of the whole experiment up to that point. This type of map is only characteristic of a low temperature propane-bitumen interaction in which some of the lower solubility components (i.e. asphaltenes) precipitate out of the propane solution. The precipitated asphaltenes are then deposited alongside the drainage paths, while the asphaltene-depleted, lower viscosity oil drains to the bottom of the cell. During some of the lower temperature experiments, it was found that the asphaltene precipitates had a tendency to block off the drainage channels and clog up the system. This area may require further investigation.

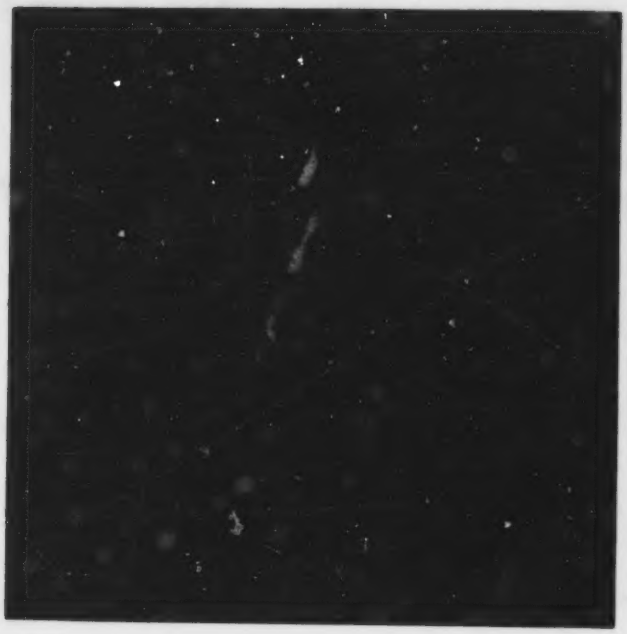
The photographs taken at 55°C (Fig.3.3.7.2) show the formation of two incipient breakthrough channels which eventually grow into the characteristic, progressively wider V-shaped channel (5/55°C to 8/55°C). There is less evidence of asphaltenes precipitation in the photographs and no instances of channel blockage were encountered.

At 90°C (Fig.3.3.7.3), the characteristic V-shaped channel is not formed (photos 4 to 6/90°C). The rate of product withdrawal (5 mℓ/hr)

was not sufficient to draw propane vapour down to the production well (see Figure 3.3.6.2). There is little, if any, asphaltene precipitation in the cell.

In another experiment at 90°C, in which the withdrawal rate was increased to 25 mℓ/hr, an initial production rate of 10.7 mℓ/hr of oil was achieved and the usual 'V'-shaped chamber was observed. This demonstrates that it is necessary to inject propane at a rate high enough to force gas solvent to the production well if the gravity mechanism is to be effective.

An analogous situation is observed in steam-assisted gravity drainage when the rate of product withdrawal is not large enough to draw the steam chamber to the base of the reservoir. In photographs 7 and 8 of Fig.3.3.7.3 the characteristic V-shaped gravity drainage interface has formed and some propane vapour is being produced. This is possible because the drainage head is low enough to yield less than 5 mℓ of liquid drainage.

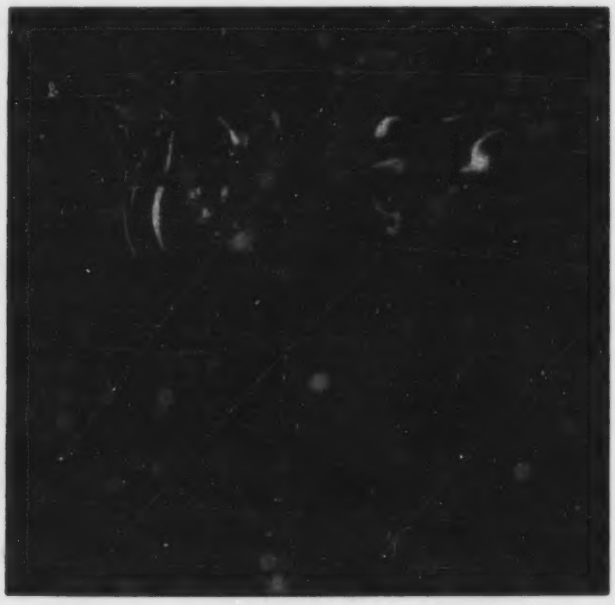


1 / 20°C

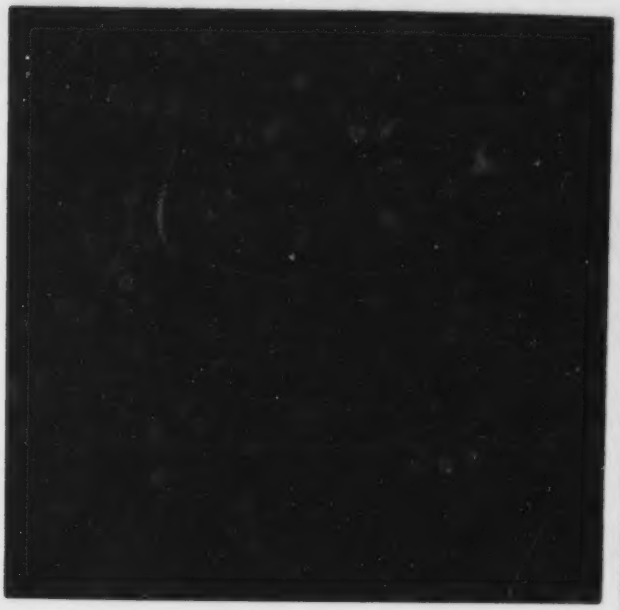
2 / 20°C

FIGURE 3.3.7.1: Point Source Experiment at 20°C (8 photographs).

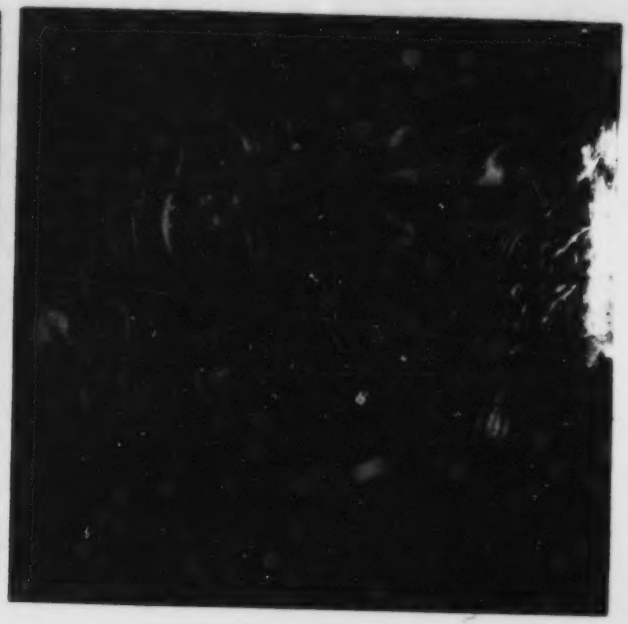
3 / 20°C



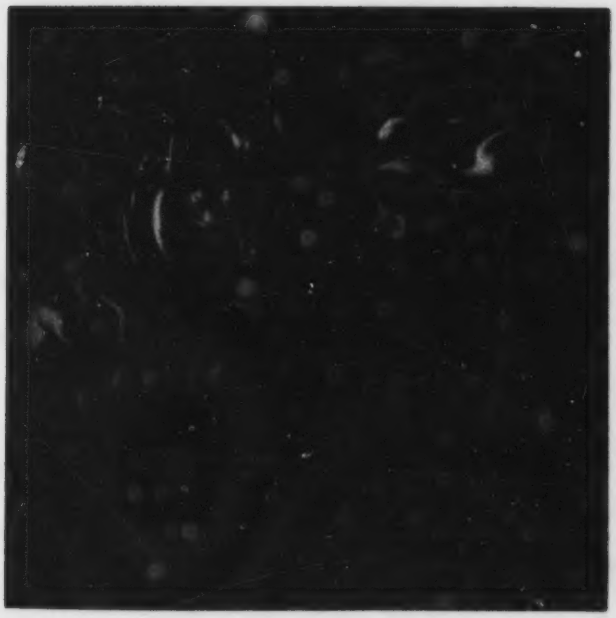
4 / 20°C



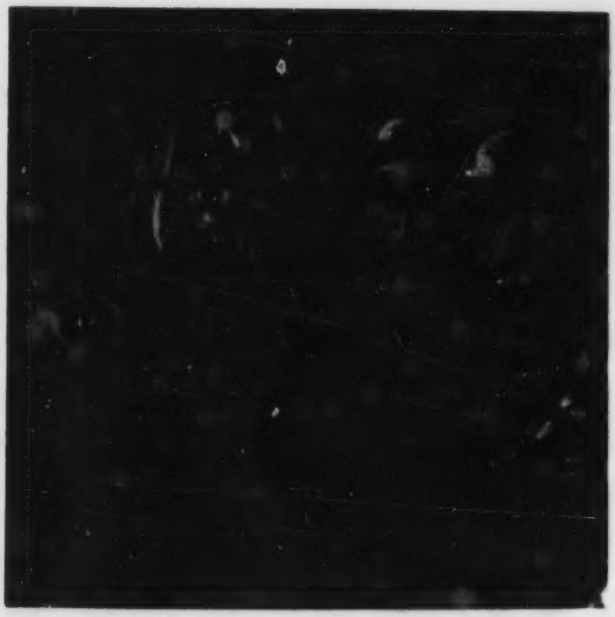
5 / 20°C



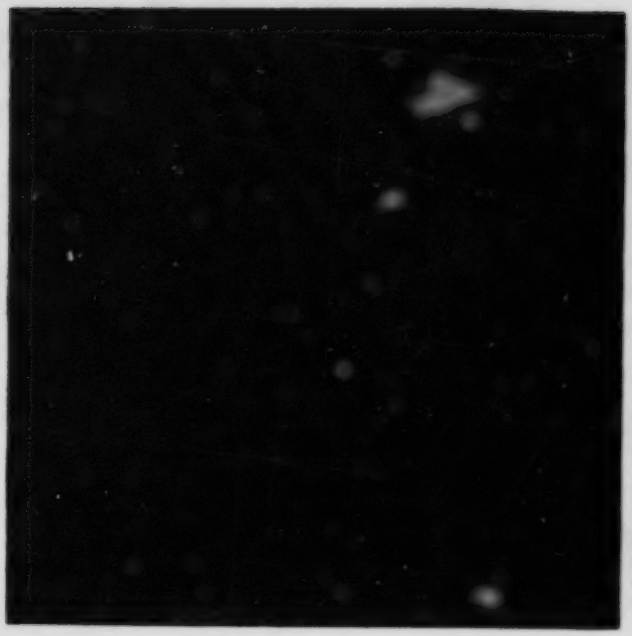
6 / 20°C



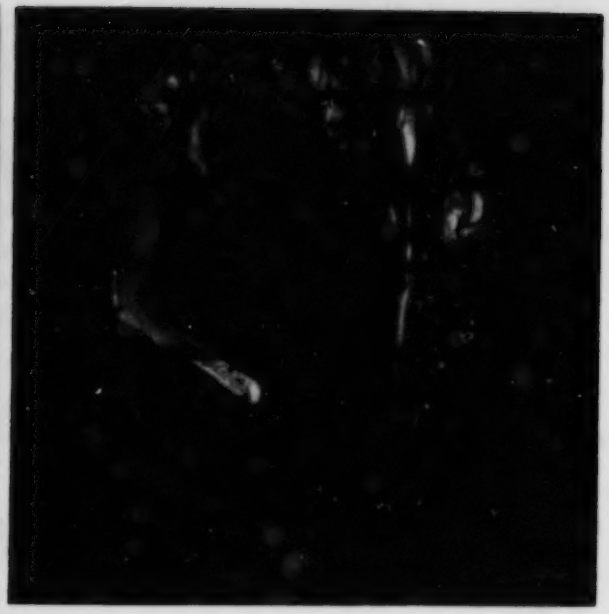
7 / 20°C



8 / 20°C

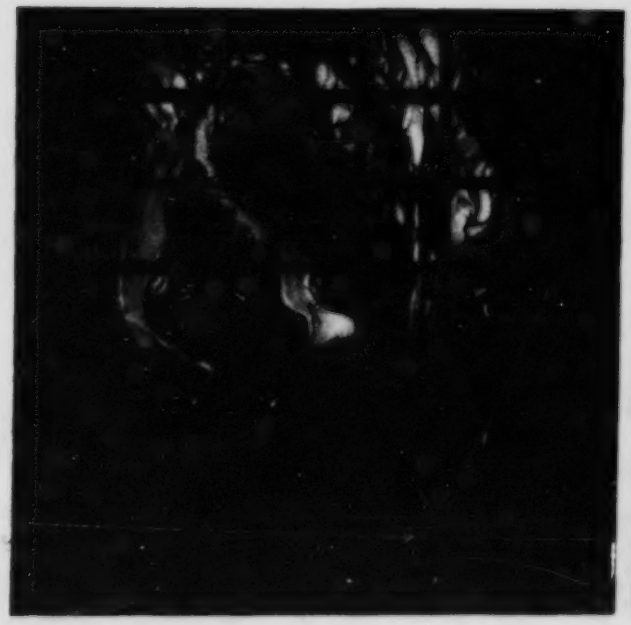


1 / 55°C

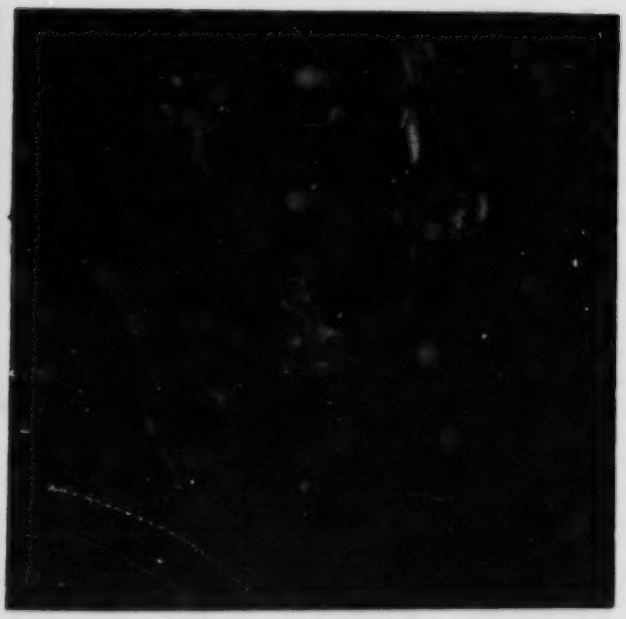


2 / 55°C

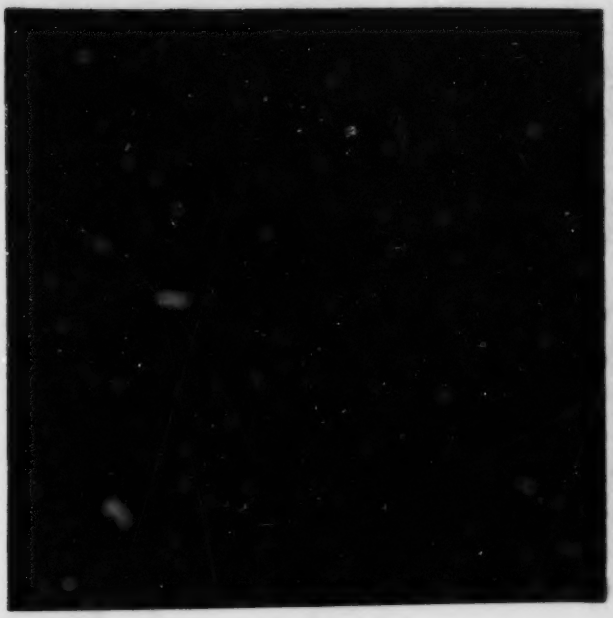
FIGURE 3.3.7.2: Point Source Cell at 55°C (total of 8 photographs)



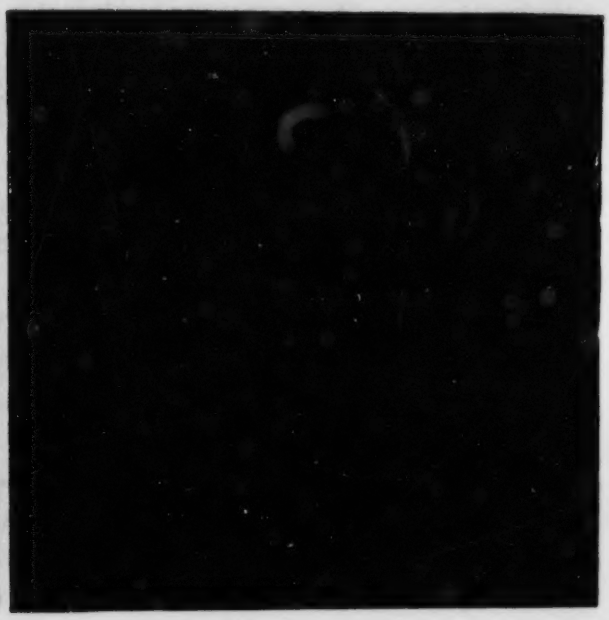
3 / 55°C



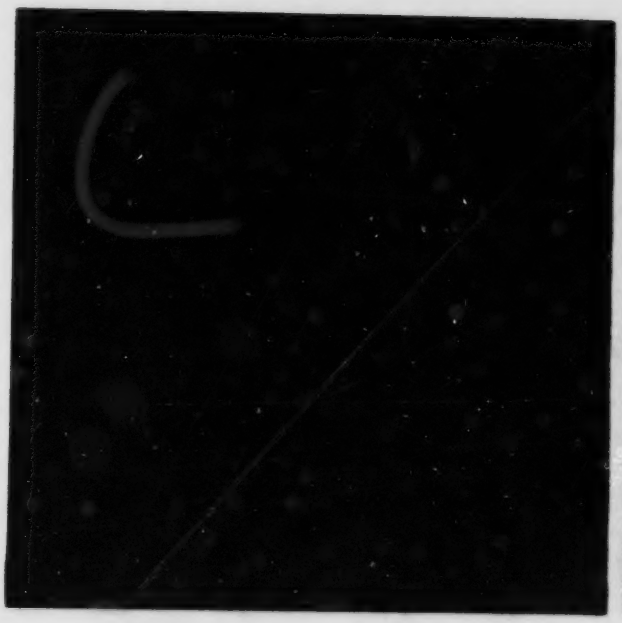
4 / 55°C



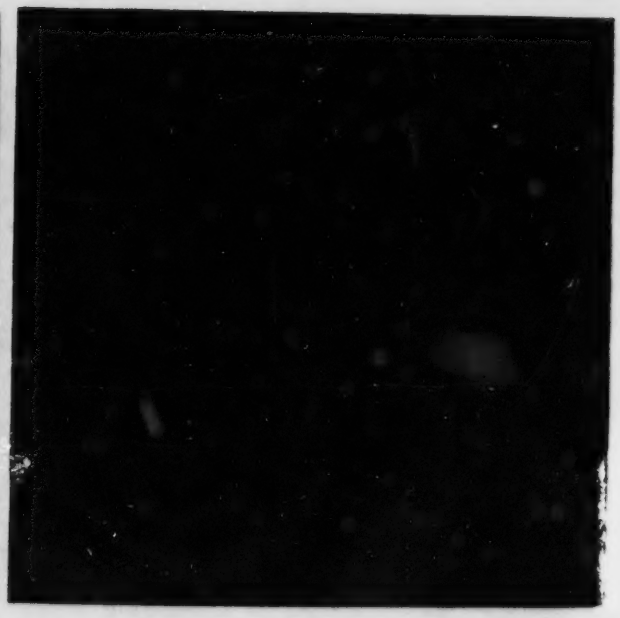
5 / 55°C



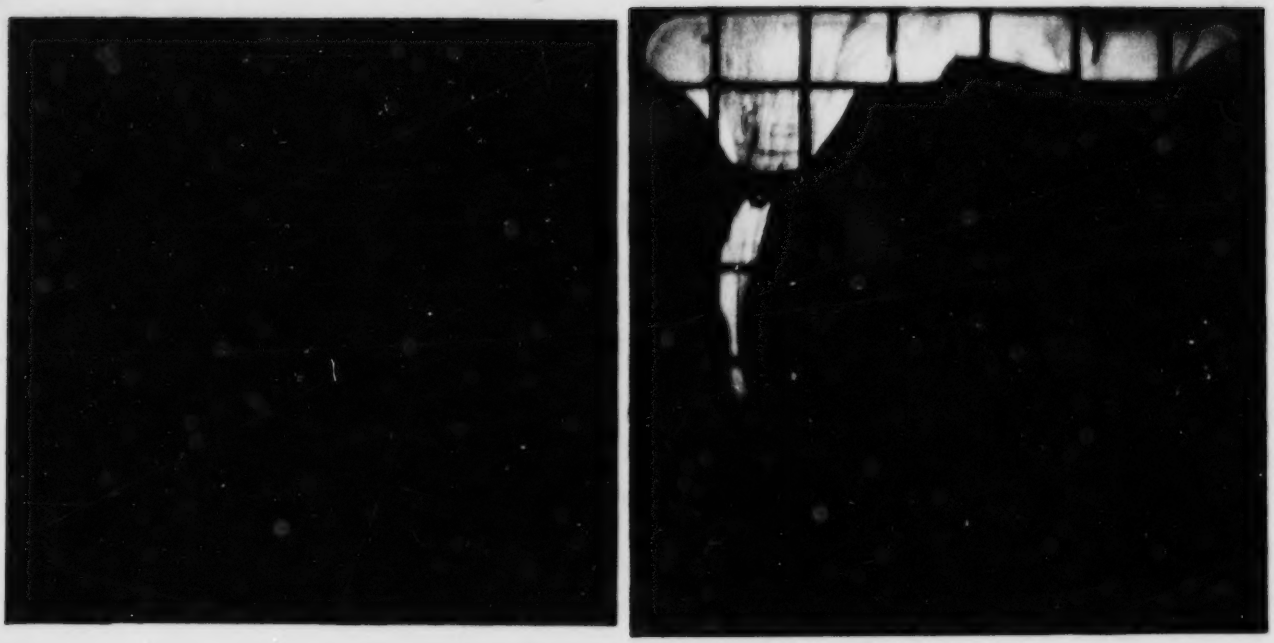
6 / 55°C



7 / 55°C



8 / 55°C



1 / 90°C

2 / 90°C

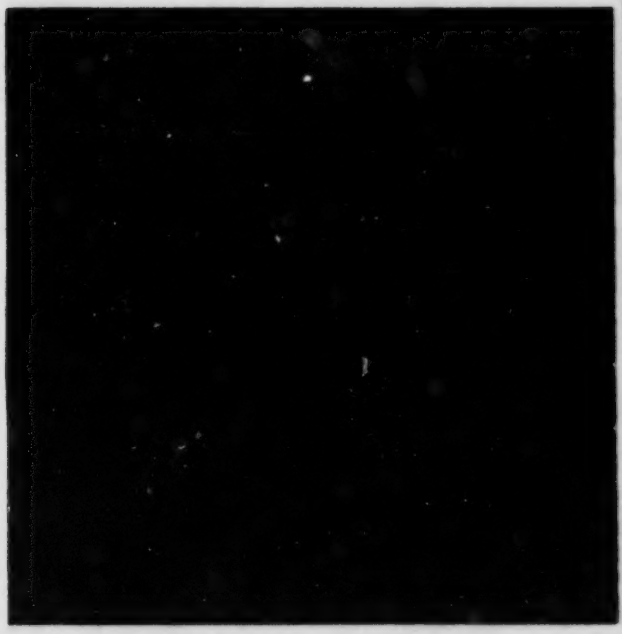
FIGURE 3.3.7.3: Point Source Experiment at 90°C (total of 8 photographs)

3 / 90°C

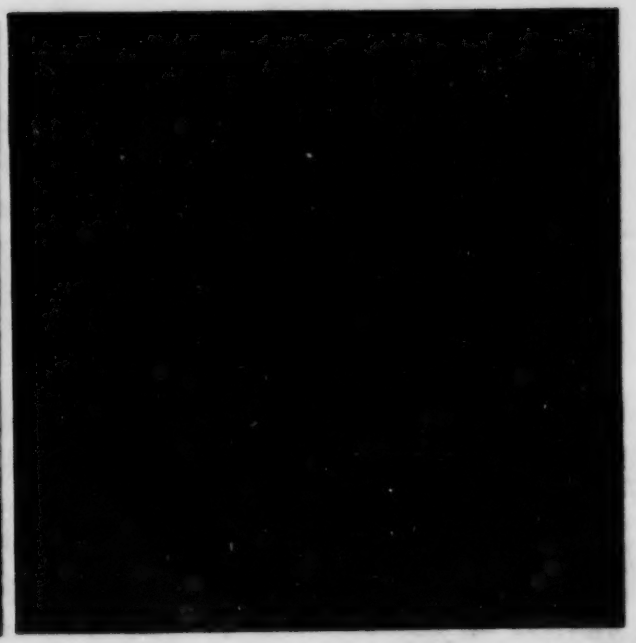
4 / 90°C

5 / 90°C

6 / 90°C



7 / 90°C



8 / 90°C

3.3.8 Initial Rates

The cumulative oil production for cell temperatures of 20, 55 and 90°C, respectively, is given in Tables 3.3.8.1, 3.3.8.2 and 3.3.8.3 and is plotted in Figures 3.3.8.1, 3.3.8.2 and 3.3.8.3. The initial production rates were obtained from the initially linear portions of the production rate curves at their respective temperatures.

Each of the eight photographs taken during a run was measured with a planimeter to determine the total photograph area and the solvent leached area in arbitrary planimeter units (APU). Using the known graticule area, APU were then converted to the cumulative oil produced (mℓ)

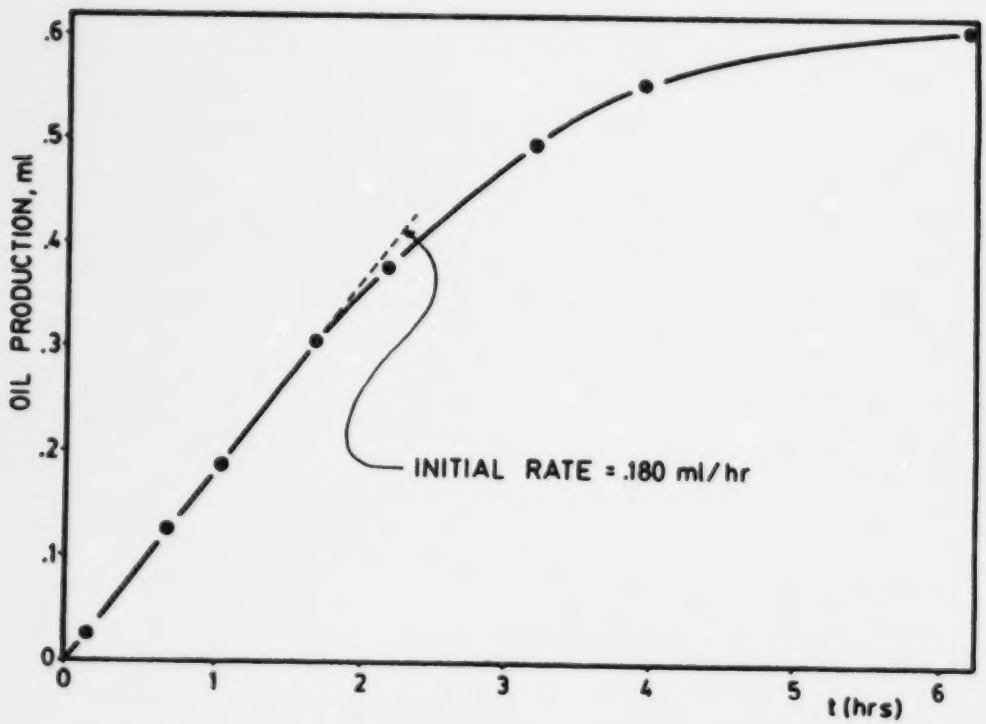


FIGURE 3.3.8.1: Rate of Oil Production at 20°C

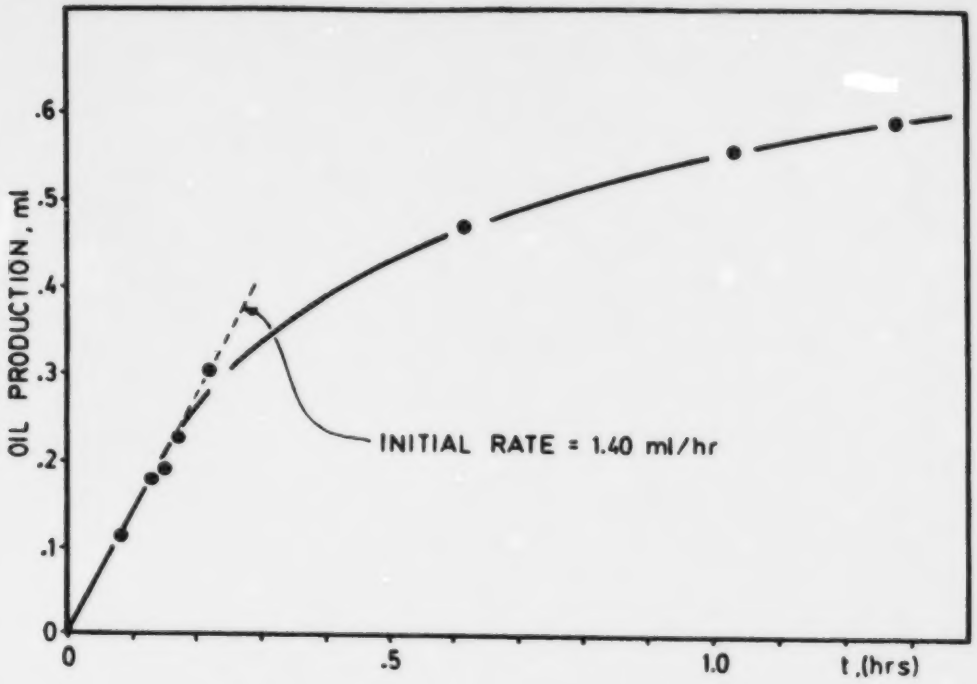


FIGURE 3.3.8.2: Rate of Oil Production at 55°C

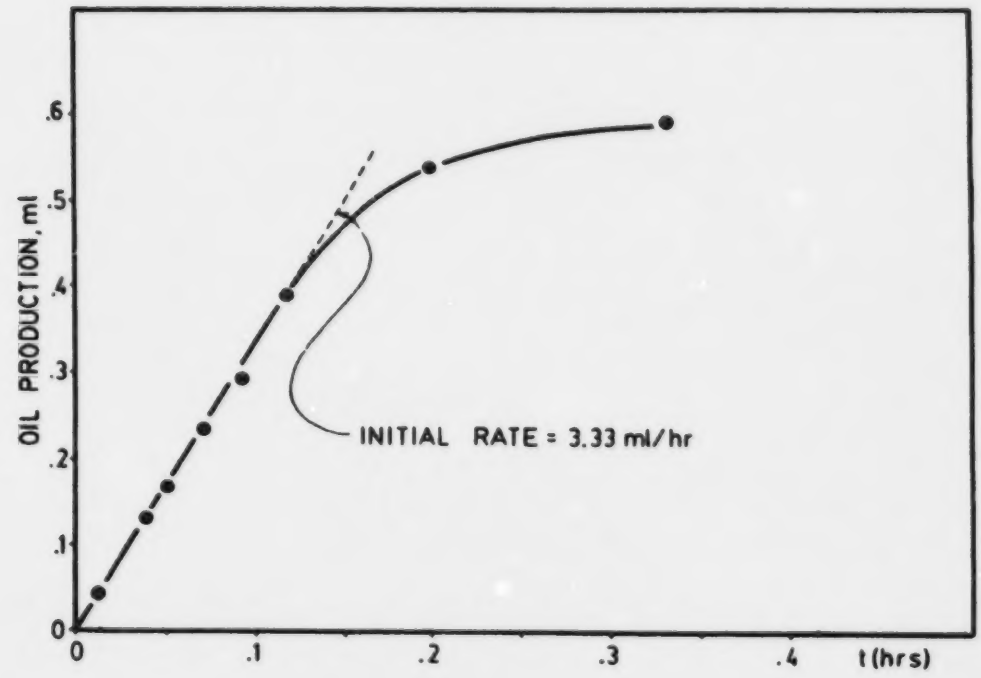


FIGURE 3.3.8.3: Rate of Oil Production at 90°C

and plotted as a function of cumulative time (hrs.). The data in Tables 3.3.8.1, 3.3.8.2 and 3.3.8.3 were obtained by evaluating areas of the 24 photographs described in Section 3.3.7. The curvatures in the oil production plots are the result of the diminishing head of oil in the cell. From our earlier work, the rate is expected to be proportional to the square root of the head.

Table 3.3.8.1: Data for Oil-Propane Drainage Process at 20°C.

Photo Number	Total Photo Area (APU)	Solvent Area (APU)	Solvent Area Cumulative Oil Produced cm^3	% Pore Volume Produced	Cumulative Time, hrs.
1	845	33	0.024	3.86	0.133
2	851	172	0.126	20.25	0.717
3	800	240	0.187	30.05	1.050
4	803	394	0.305	49.01	1.717
5	818	496	0.377	60.58	2.217
6	838	668	0.496	79.70	3.217
7	828	739	0.555	89.19	3.967
8	838	814	0.604	97.06	6.217

Rate of withdrawal = 5 mℓ/hr

Hele-Shaw cell volume = 0.6223 cm^3 ρ_o = 0.9717 g/cm^3

Initial oil production rate = 0.180 cm^3/hr

Cell temperature = 20°C $\rho_{C_3}(v)$ = 0.01541 g/cm^3

Cell pressure = 108 psig

Propane vapour molar volume = 2855.6 cm^3/mol at the cell temperature and pressure

Table 3.3.8.2: Data for Oil-Propane Drainage Process at 55°C.

Photo Number	Total Photo Area (APU)	Solvent Area (APU)	Solvent Area Cumulative Oil Produced cm^3	% Pore Volume Produced	Cumulative Time, hrs.
1	743	134	0.112	18.00	0.083
2	778	226	0.181	29.09	0.133
3	815	249	0.190	30.53	0.150
4	915	298	0.228	36.64	0.167
5	815	395	0.302	48.53	0.217
6	807	609	0.470	75.53	0.617
7	801	717	0.557	89.51	1.033
8	807	765	0.590	94.81	1.283

Rate of withdrawal = 5 mℓ/hr

Hele-Shaw cell volume = 0.6223 cm^3 ρ_o = 0.9588 g/cm^3

Initial oil production rate = 0.140 cm^3/hr

Cell temperature = 55°C $\rho_{C_3}(v)$ = 0.03714 g/cm^3

Cell pressure = 262 psig

Propane vapour molar volume = 1184.8 cm^3/mol at the cell temperature and pressure

Table 3.3.8.3: Data for Oil-Propane Drainage Process at 90°C.

Photo Number	Total Photo Area (APU)	Solvent Area (APU)	Solvent Area Cumulative Oil Produced cm^3	% Pore Volume Produced	Cumulative Time, hrs.
1	865	50	0.036	5.79	0.017
2	862	178	0.129	20.73	0.038
3	868	231	0.166	26.68	0.050
4	860	322	0.233	37.44	0.071
5	867	405	0.291	46.76	0.092
6	870	546	0.391	62.83	0.117
7	868	750	0.538	86.45	0.200
8	868	825	0.591	94.97	0.333

Rate of withdrawal = 5 mℓ/hr

Hele-Shaw cell volume = 0.6223 cm^3 ρ_o = 0.9383 g/cm^3

Initial oil production rate = 3.33 cm^3/hr

Cell temperature = 90°C $\rho_{C_3}(v)$ = 0.07342 g/cm^3

Cell pressure = 510 psig

Propane vapour molar volume = 599.3 cm^3/mol at the cell temperature and pressure

4. Propane Injection into a Packed Cell

4.1 Development of the Experimental Method

The oil drainage experiments obtained with the point source Hele-Shaw cell relied on an outside constant source of heat to establish the equilibrium conditions inside the pressure vessel where the cell was located and drained. In order to move one step closer to an actual reservoir, it was desirable to design and construct a packed cell and eliminate the external heating bath. All the heat supplied in the experiments described in this section (4) came from the sensible heat and from the latent heat of condensation (dissolution) of injected propane. In the subsequent experiments (reported in Section 5) the heat was supplied by means of simultaneous injection of hot water with the propane. This lead to the concept of the VAPEX process; this will be discussed later. In the sections 4.1.1 through 4.2 the packed cell will be described and experiments will be reported in which pre-heated propane but no water was injected into the packed cell.

4.1.1 The design of the packed cell

The new packed cell was designed to fit into the existing pressure vessel. It was made of a reinforced phenolic resin to minimize heat transfer by thermal conductivity to or from the walls of the pressure vessel and was equipped with 7 thermocouples located in the back wall. A 7 x 7 cm plexiglass window (inert to propane) facilitated viewing of the spreading solvent chamber when required. The inside dimensions of the cell were 7 x 7 x 2.54 cm^3 (see photos in Figs 4.1.1.1 and 4.1.1.3).

The injection port was at the top center while the producer was located at the bottom center of the inside of the cell. Two 100 mesh wire discs covered the injection and production ports to prevent their

accidental blockage by the glass beads. Several views of the cell and the apparatus are presented in the following photographs.

FIGURE 4.1.1.1: PHOTOGRAPH OF THE NEW CELL FILLED WITH 1 mm GLASS BEADS

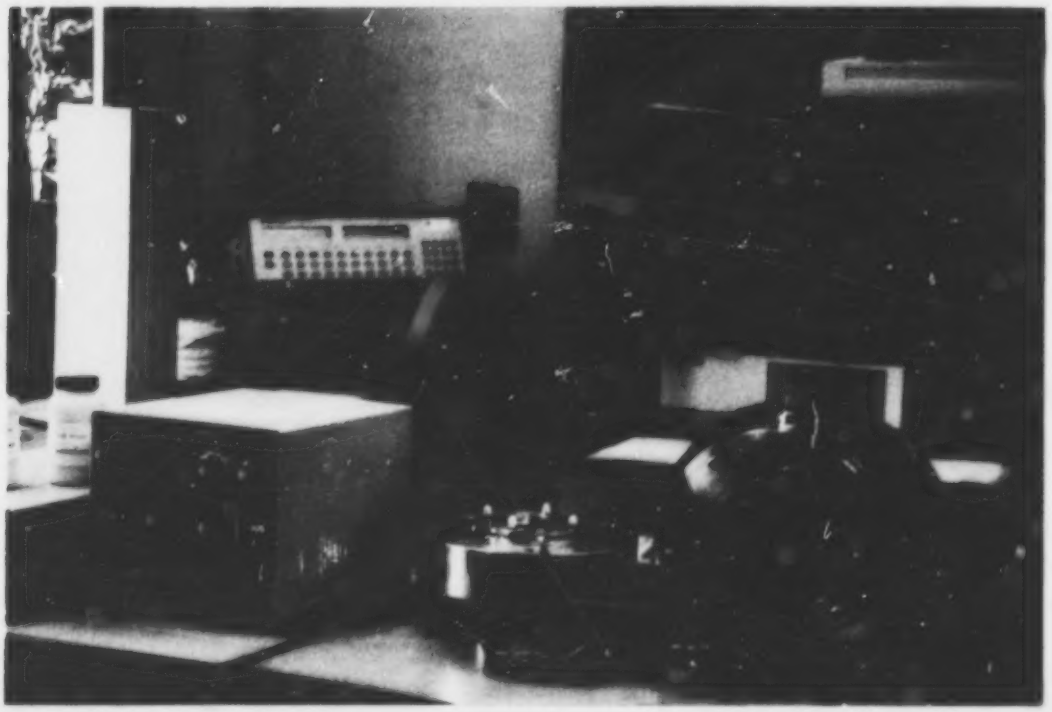


FIGURE 4.1.1.2: OVERALL VIEW OF THE EXPERIMENTAL SETUP

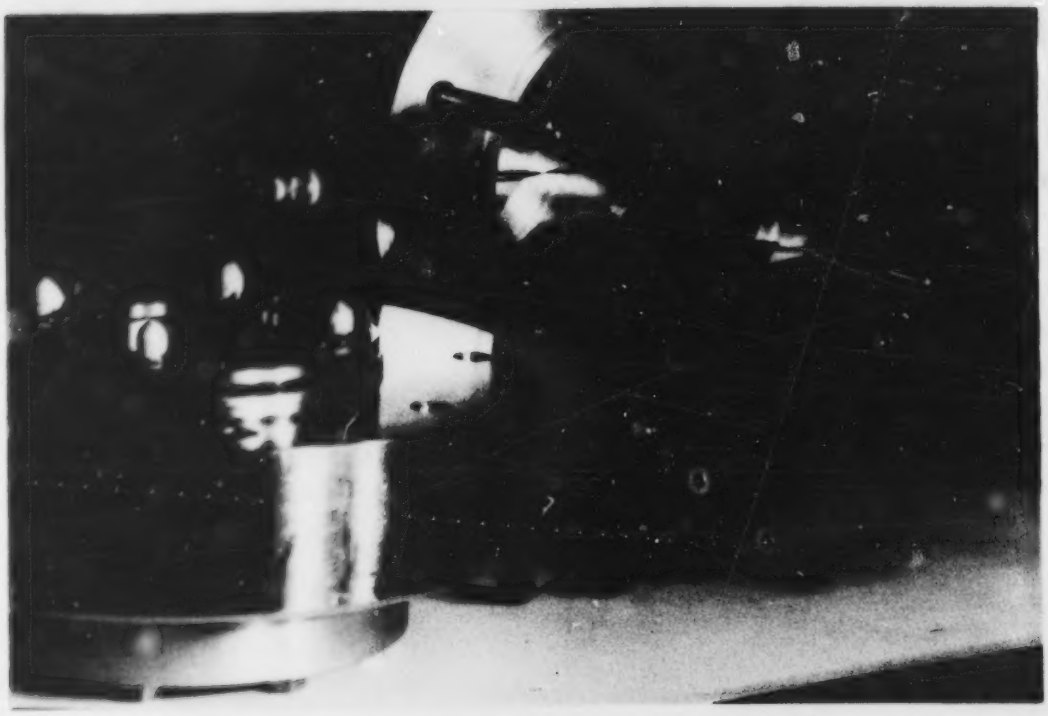


FIGURE 4.1.1.3: FRONT OF THE CELL WITH THERMOCOUPLES

FIGURE 4.1.1.4: REAR OF THE CELL WITH CONNECTORS

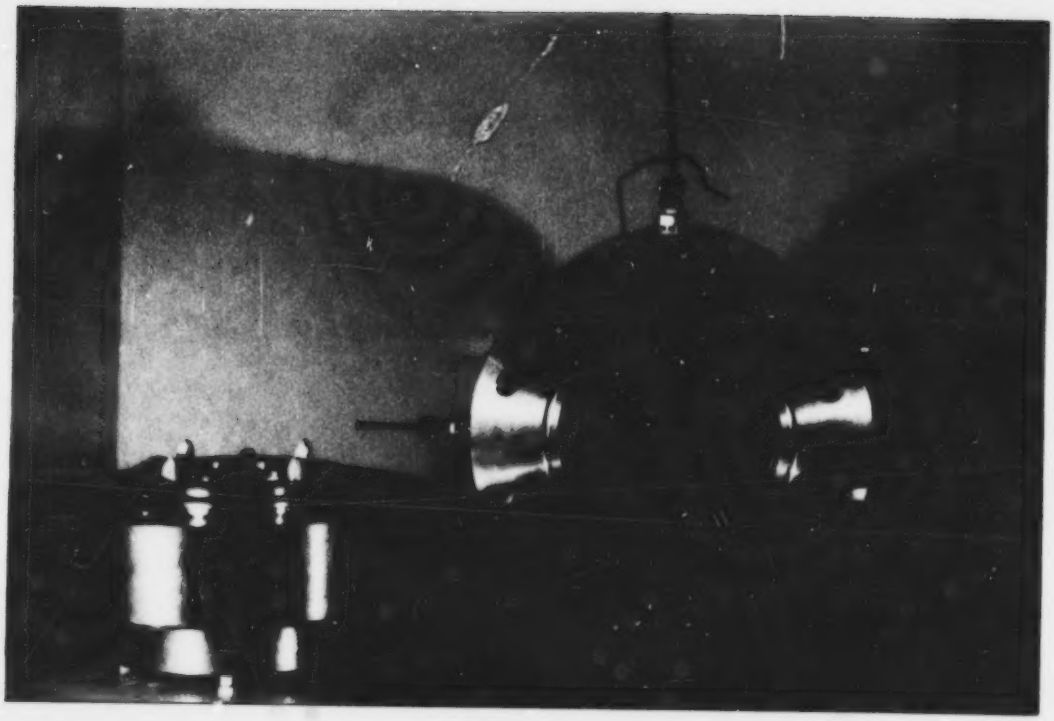


FIGURE 4.1.1.5: CELL INSIDE THE PRESSURE VESSEL

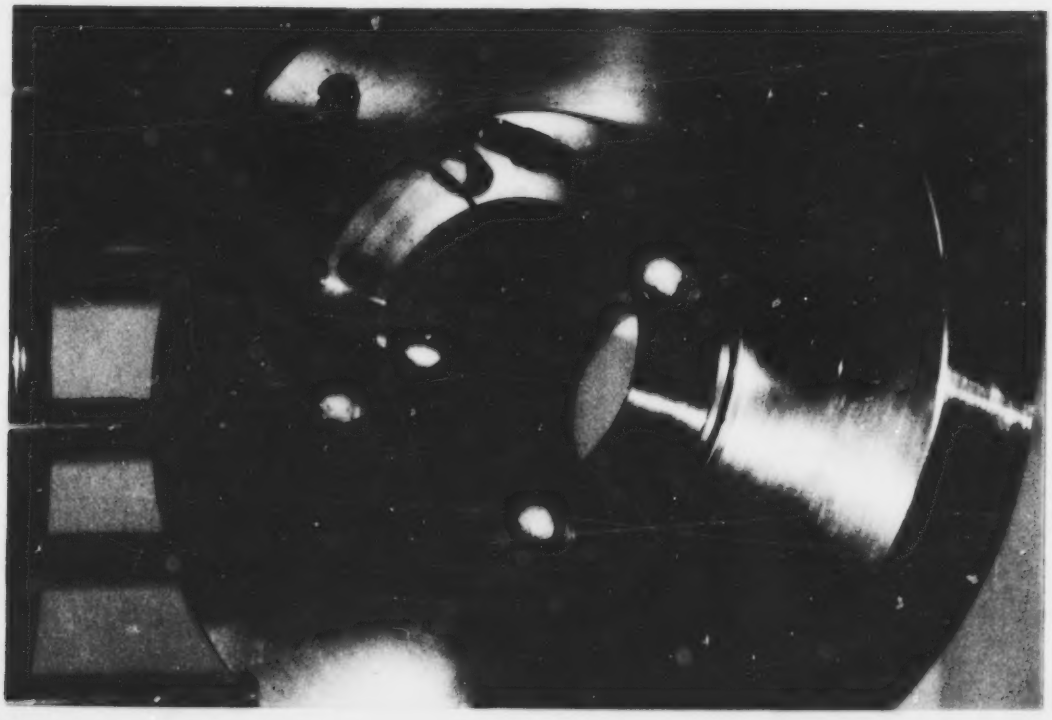


FIGURE 4.1.1.6: CELL ILLUMINATION

4.1.2 Permeability and Time Scaling for the Packed Cell

Using data from ref. [3] we have developed the following correlation for the permeability of a bed of uniform spheres packed to a porosity of 40 percent:

$$\left(\frac{k}{d^2}\right)_{average} \approx 1150 \qquad (4.1.2.1)$$

where k is the permeability of the bed in darcies, and

d is the diameter of the packing beads in mm.

The cell in Fig.4.1.1.1 was vibro-packed with 1 mm glass beads (ie. d=1 mm) to obtain the maximum compaction packing corresponding to a porosity of 39.1 percent. According to Eq.(4.1.2.1), this corresponds to the cell permeability of 1150 darcy. The field permeability was chosen 5 darcy and the average change in oil saturation obtained from experiments in our model was about 0.86. The model and field parameters are summarized below:

k_M= 1150 darcy	k_F= 5 darcy
ϕ_M= 0.391	ϕ_F= 0.35
$(\Delta S_o)_M$= 0.86	$(\Delta S_o)_F$= 0.86
H_M= 0.07 m	

Substituting these values into the scaling equation, Eq.(3.3.5.6), and solving for the reservoir height reveals that the scaled model represents a vertical cross section through a 12.9 m thick reservoir with a permeability of 5 darcy.

The time scaling may be obtained from Eq.(3.3.5.5), and for the packed cell

1 model hour = 4.33 years in the field	4.1.2.2

The initial volume of oil in the cell was about 48.7 mℓ. A freshly packed cell was filled by upward displacement at 40°C with the Tangleflags North heavy oil prior to every experiment.

4.1.3 Apparatus for Hot Propane Injection

A diagram of the packed cell and a schematic of the apparatus are given in Figures 4.1.3.1 and 4.1.3.2. The propane cylinder and the oil-gas separator were weighed continuously to enable the determination of the gas/oil ratio as a function of time and also the plotting of the oil production curve. The produced propane gas was collected in an inverted cylinder and its volume checked against the weight loss of the propane cylinder. The saturated propane gas was injected at constant temperatures ranging from 20 to 80°C.

The propane cylinder was heated about 5°C above the temperature of the heat box to compensate for any heat losses in the carrying conduit. The filled cell was initially at 20°C but increased in temperature during the course of an experiment (Table 4.2.1). The average cell temperatures are plotted in Figure 4.2.3. The large mass of the pressure vessel effectively insulated the cell from the elevated temperature inside the heat box for the duration of the experiment (2-3 hours) and the small increase in the cell temperature was almost entirely due to the latent heat of dissolution and sensible heat of

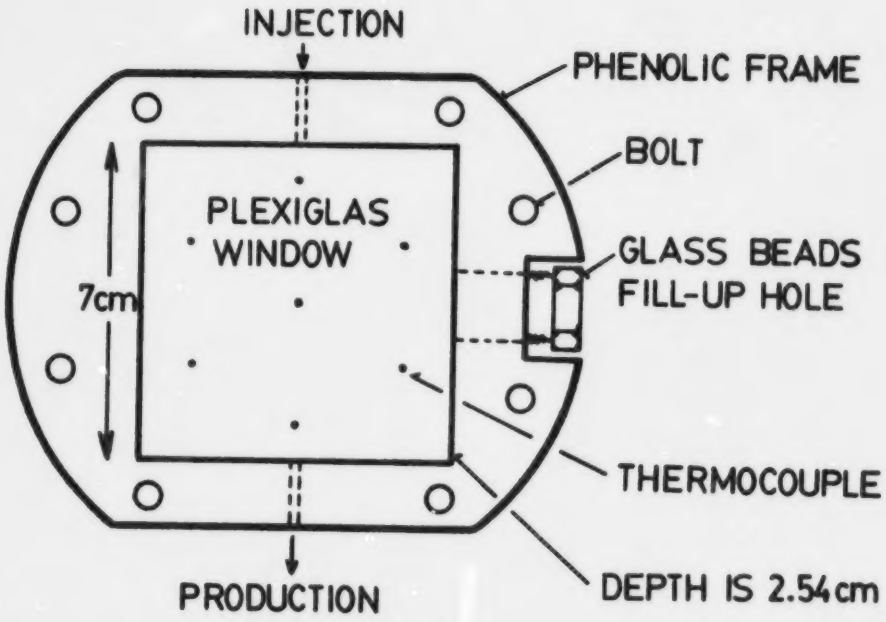


FIGURE 4.1.3.1: A Diagram of the Visual Scaled Packed Cell With 7 Thermocouples.

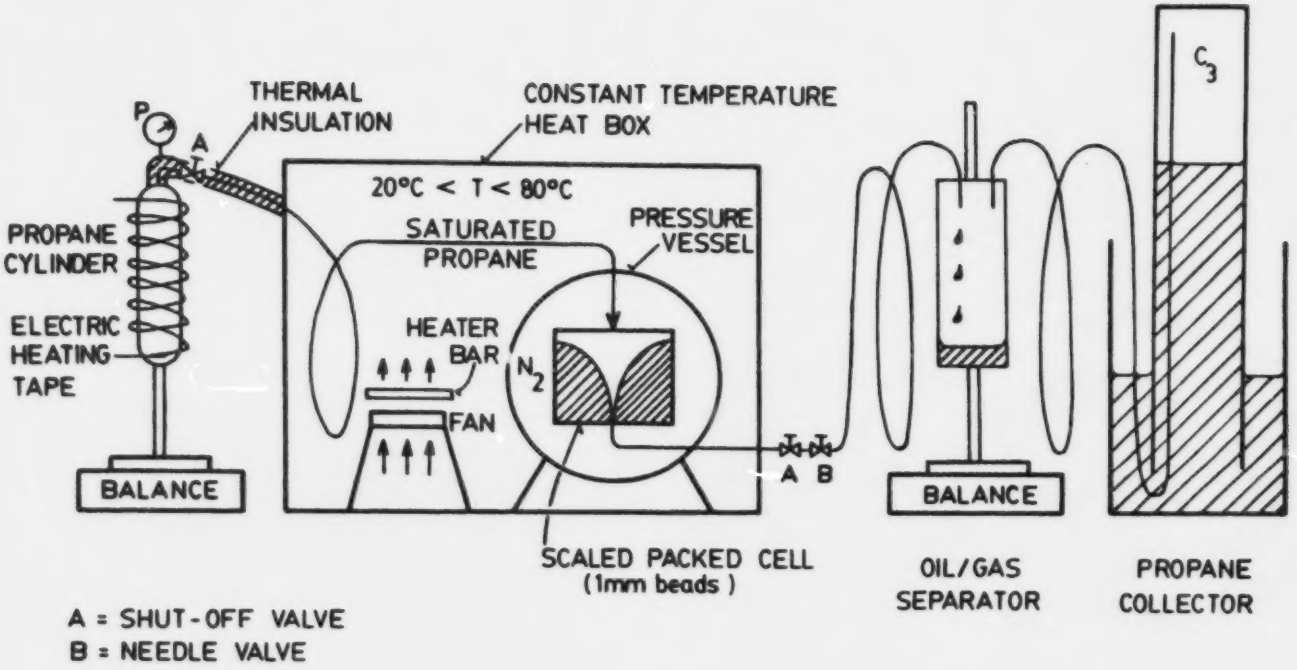


FIGURE 4.1.3.2: Schematics of the Experimental Set-up for Injecting Saturated Hot Propane into a Scaled Packed Cell.

(7 experiments at temperatures ranging from 20°C to 80°C)

propane. An excessive comsumption of propane was avoided by throttling its flow with a fine needle valve located between the oil-gas separator and the pressure vessel. The results of 7 runs with propane injection temperatures of 20, 27, 40, 50, 67, 70 and 80°C that were carried out in this experimental apparatus are discussed below.

4.2 Discussion of Experimental Results with Hot Propane Injection

A summary of experimental results is given in Table 4.2.1 and Figures 4.2.1 to 4.2.4. Results of individual runs are listed in Appendix A (Figures A5a to A11b).

TABLE 4.2.1: Oil Production Rates and Gas-to-Oil Ratios as a Function of Propane Injection Temperature.

Run number	Propane inj.temp. (°C)	Cell press. (psi)	Cell temp. (°C)	Init.oil prod.rate (ml/hr)	Cumul. gas-to-oil (g/g)
1	20	105	24	11.73	0.6
2	27	125	27	33.8	0.6
3	40	180	30	29.5	1.0
4	50	225	32	23.8	1.7
5	67	340	30	17.8	1.85
6	70	350	33	17.5	1.45
7	80	400	30	14.5	1.5

The results in Figure 4.2.1 show that the initial oil production rate from the packed cell passes through a maximum which, for the Tangleflags North heavy oil (see Appendix A, Figures A2 and A4), occurs at about 30°C. This figure indicates that the rate increases with the propane injection temperature but only when the experimental conditions allow a vapourized solvent chamber to form. If the vapour condenses partially or fully in the cell, the rate of the extraction process

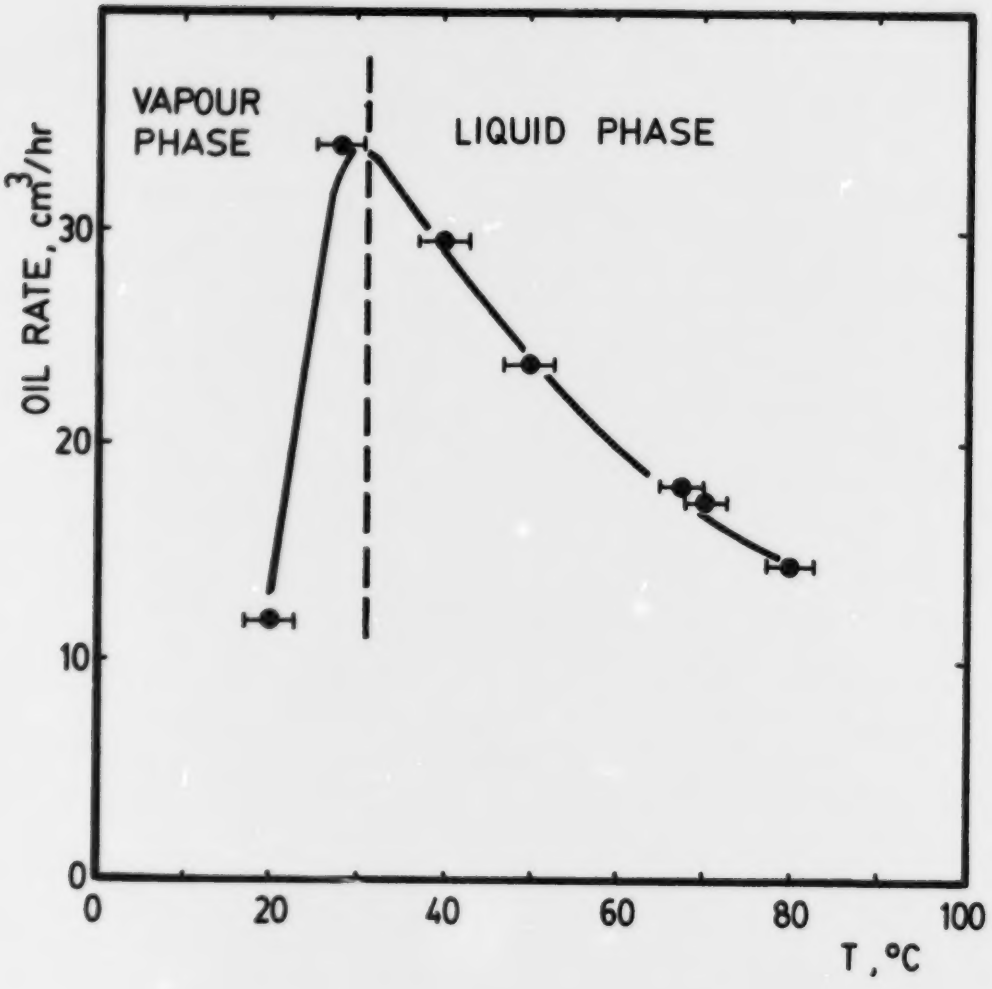


FIGURE 4.2.1: Oil Production Rates as a Function of Propane Injection Temperature for Hot Propane Injection into the Scaled Packed Cell. Data from Table 4.2.1.

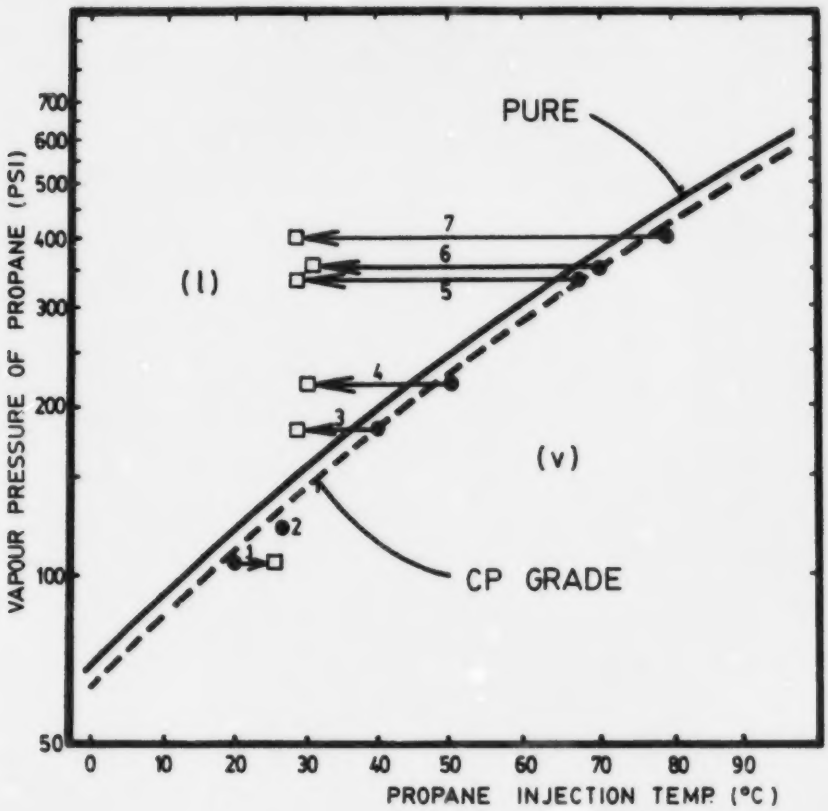


FIGURE 4.2.2: Effect of cell temperature on propane phase change (indicated by arrows) during a hot propane vapour injection into a cold packed cell for 7 runs in Table 4.2.1. The squares denote the cell temperature to which the propane was cooled and the full circles denote the propane injection temperature.

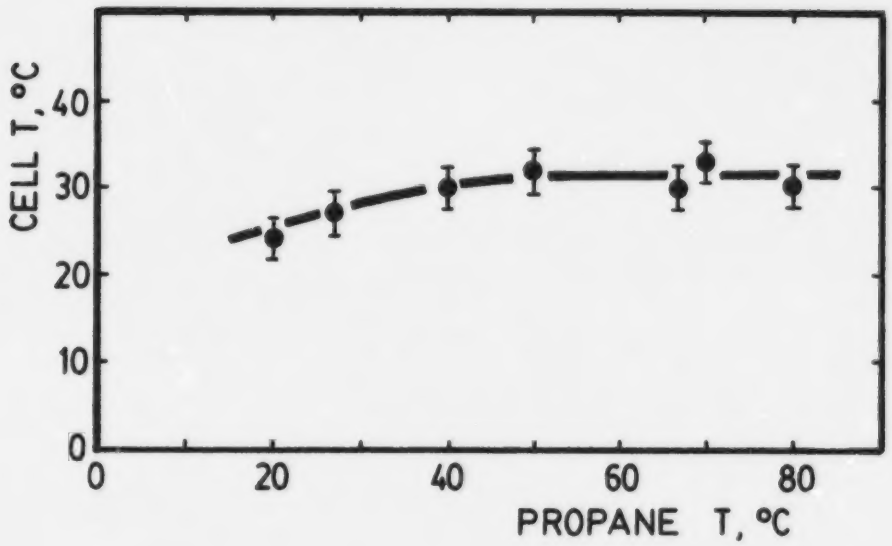


FIGURE 4.2.3: Average Cell Temperature as a Function of Propane Injection Temperature for the Scaled Packed Cell. Data from Table 4.2.1

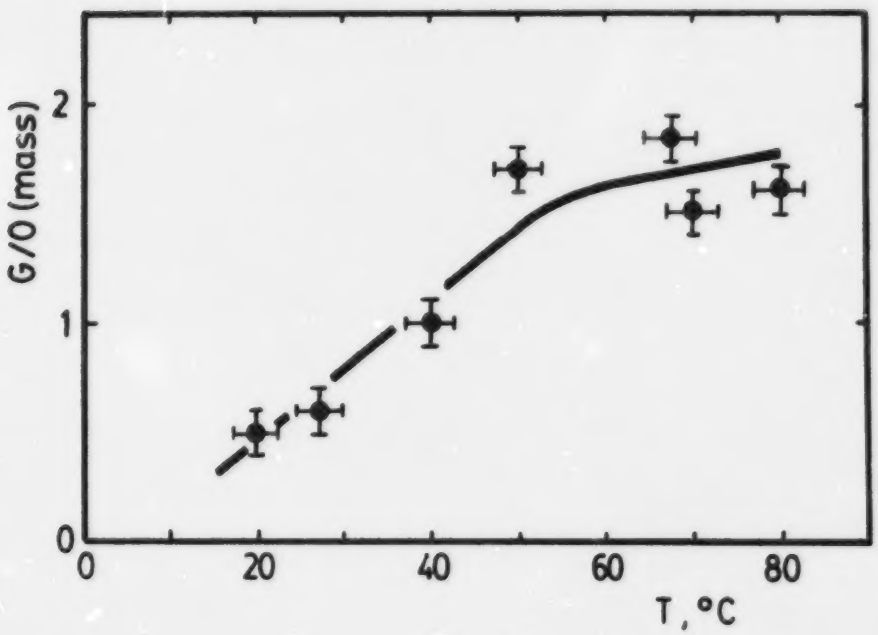


FIGURE 4.2.4: Cumulative Propane-Oil Ratios (mass) as a Function of Propane Injection Temperature for the Scaled Packed Cell.

decreases irrespective of the vapour injection temperature. As indicated in Fig.4.2.3, this is because the heat capacity and the heat of dissolution of the injected propane vapour are insufficient to raise the cell temperature enough to prevent condensation. The process therefore requires the injection of a heat carrier, such as hot water. This observation led to the development of the Vapex process as described later.

The phase change during the injection of hot propane vapour into a cold packed cell, which is responsible for the decrease of the oil recovery rate from the cell, is illustrated in Fig.4.2.2. This figure contains a vapour pressure curve for the CP grade propane used in our experimental work. The full circles represent the initial conditions at which propane vapour injection occurred and the squares represent the cell temperature to which the propane vapour was cooled (or warmed) at a constant pressure. For runs 3 to 7 this cooling is accompanied by a phase change resulting in a decreasing oil drainage rate as earlier indicated in Fig.4.2.1. Since our CP grade propane contained amounts of other condensable hydrocarbon vapours, this phase change took place over an interval of temperatures and the decreasing rate in Fig.4.2.1 is due to the increasing proportion of liquid phase in the cell.

The gas-to-oil ratio for the 7 runs is plotted in Fig.4.2.4. It increases as a result of both the lower oil recovery rates and poor control over the 3-phase flow which is exacerbated at higher cell pressures.

For the production rate at 27^{o}C, about 70 percent oil was recovered in 1 hour. This indicates, Eq.(4.1.2.2), that in a 12.9 m thick 5 darcy reservoir, a similar recovery can be achieved in 4.33 years.

5. Simultaneous Hot Water/Propane Injection into the Packed Cell: Development of the Vapex Process.

5.1 Initial Experiments With a Single Pump.

In these experiments, hot water from an ISCO pump was injected continuously into the packed cell for the duration of the experiment. However, included in the ISCO water pump circuit was a pressure transducer that would stop the pump if a pre-set pressure was exceeded. This control feature was necessary to protect the cell against the damage that would result from injecting fluids above the cell confining (ie. overburden) pressure of nitrogen.

The experimental set-up was similar to that in Figure 4.1.3.2 with the addition of hot water injected from a syringe-type ISCO pump. There was a non-return valve in the water line, to prevent propane passing from the cylinder directly into the pump, and both streams merged just before the pressure vessel.

The hot water flood produced a breakthrough of water, as observed outside the pressure vessel, within, typically, the first 15 to 20 minutes. Very little oil was displaced during the period preceding breakthrough. The breakthrough was produced by high pressure (200-400 psi) injection but the rate was very small; after breakthrough water injection was easier.

Propane was introduced about 1 hour after the breakthrough and the production was regulated with a fine metering valve. The amount of water injected during the waterflood was estimated from the volume scale on the ISCO Syringe-Type Pump and both the propane consumption and total production were obtained by monitoring weight increments (or decrements) on laboratory balances as shown in Fig.4.1.3.2.

Two runs were completed with this experimental set-up and the

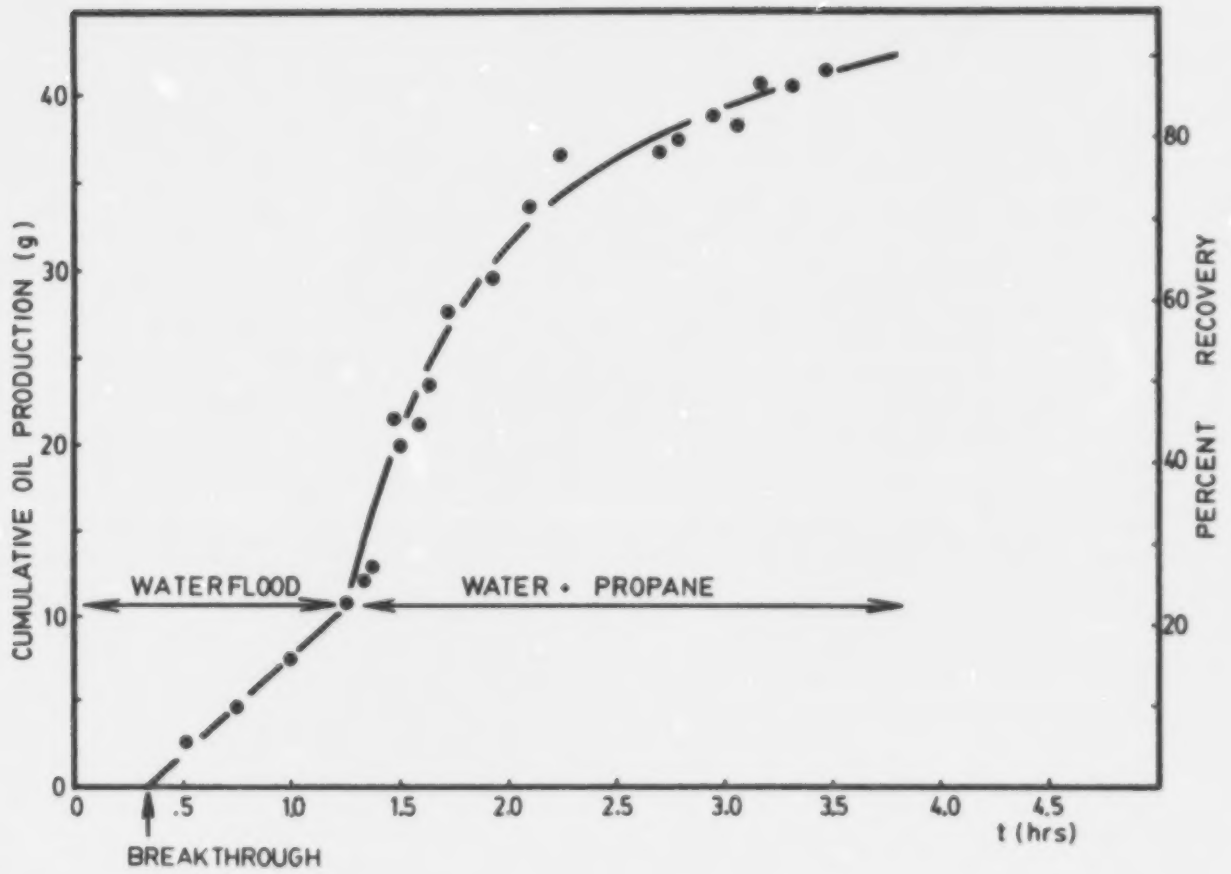


FIGURE 5.1.1: The Effect of Propane Injection on the Cumulative Oil Production from a Hot Waterflood. The Average Cell Temperature was about 30°C. Single Pump Injection.

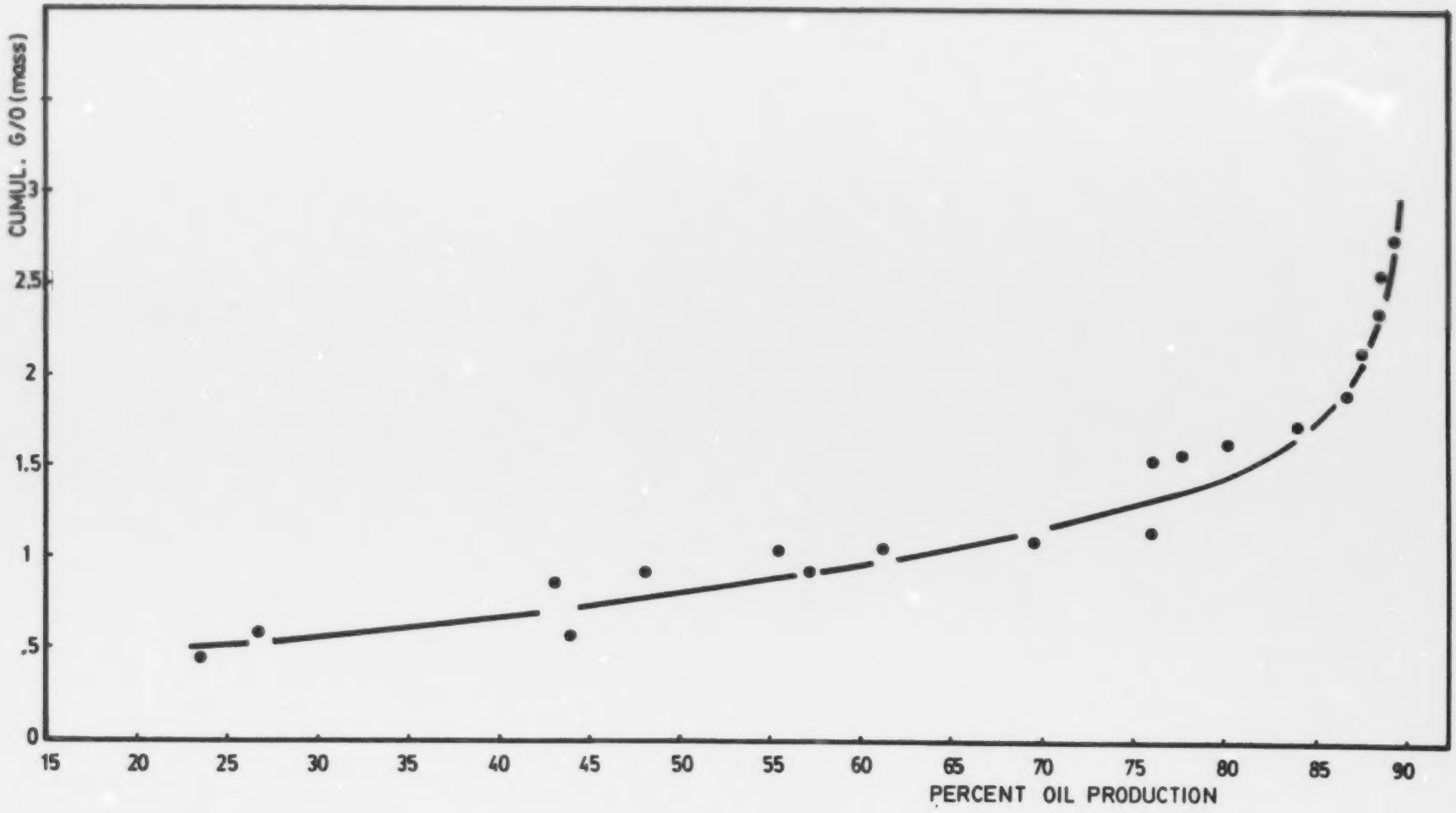


FIGURE 5.1.2: Cumulative Gas-Oil Ratio for Hot Water and Propane Injection Into a Scaled Packed Cell. Refers to Fig.5.1.1.

results were similar. A set of results for the first run is given in Figures 5.1.1 and 5.1.2.

In this experiment, hot water at 90°C and 400 psi was injected into the packed cell causing a water breakthrough after 20 minutes. The confining pressure of nitrogen around the cell protected the cell from damage. After breakthrough, the cell pressure varied between, typically, 0 and 100 psig and the confining pressure was lowered to accommodate this change. Propane injection was initiated at 77 minutes after the start of the experiment; at this time the cell thermocouples indicated an increase in temperature from the initial 20°C to about 30-35°C and this was maintained throughout the experiment. The main reason for the low cell temperature was the fact that, in spite of thermal insulation, the water lost heat during the passage through the massive wall of the pressure vessel.

The results show that the addition of propane to the injection water enhanced the oil recovery process markedly. The rate of recovery increased threefold and about 80 percent of the original oil in place was recovered in 2 hours. The two runs revealed that improved control over the experimental conditions was desirable; in particular, the rate of propane injection required more accurate control and the method for oil determination needed improvement also. These shortcomings were eliminated by the inclusion of a second injection pump (ie. for propane) in the apparatus and by analyzing individual samples for water as described in the next section.

5.2 Metering the Water and Propane Individually Using Two Pumps

5.2.1 Oil Determined Visually from Centrifuged Samples

In these experiments both water and propane were injected at controlled rates using the apparatus shown in Fig.5.2.1.1. At the start of each experiment except #6 (this was at the highest temperature) the oil production rate dropped nearly to zero after an hour or so. When this happened the propane vapour injection was started while the hot water injection was continued. This behaviour is shown by the recovery data for run #3 which are plotted in Fig.5.2.1.2. The experimental conditions were chosen so that the oil was displaced by propane in the vapour phase at or near its dew point.

The results are plotted individually in the Appendix B and are summarized in the following table and Fig.5.2.1.3.

TABLE 5.2.1.1
SUMMARY OF SEVEN RUNS FOR HOT WATER-PROPANE INJECTION

Run No	Average Cell Conditions		Percent Recovery of Oil		Oil Prod.Rate just after propane Injection (g/hr)
	T(°C)	P(psi)	Water	Water/Propane	
1	32	145	31	88	33.3
2	34	150	15	85	37.0
3	36	150	4	84	41.1
4	47	210	22	83	63.8
5	43	210	20	93	52.6
6	67	350	38	84	(64)[3]
7	35	150	20	85	38.0

As seen from Fig.5.2.1.3, the oil recovery rate just after the injection of propane vapour increases with temperature. This result is a fundamentally different from that shown in Fig.4.2.1. We consider that in the case of hot water/propane, the hot water near the bottom of

[3]Not well defined; not plotted in Fig.5.2.1.2.

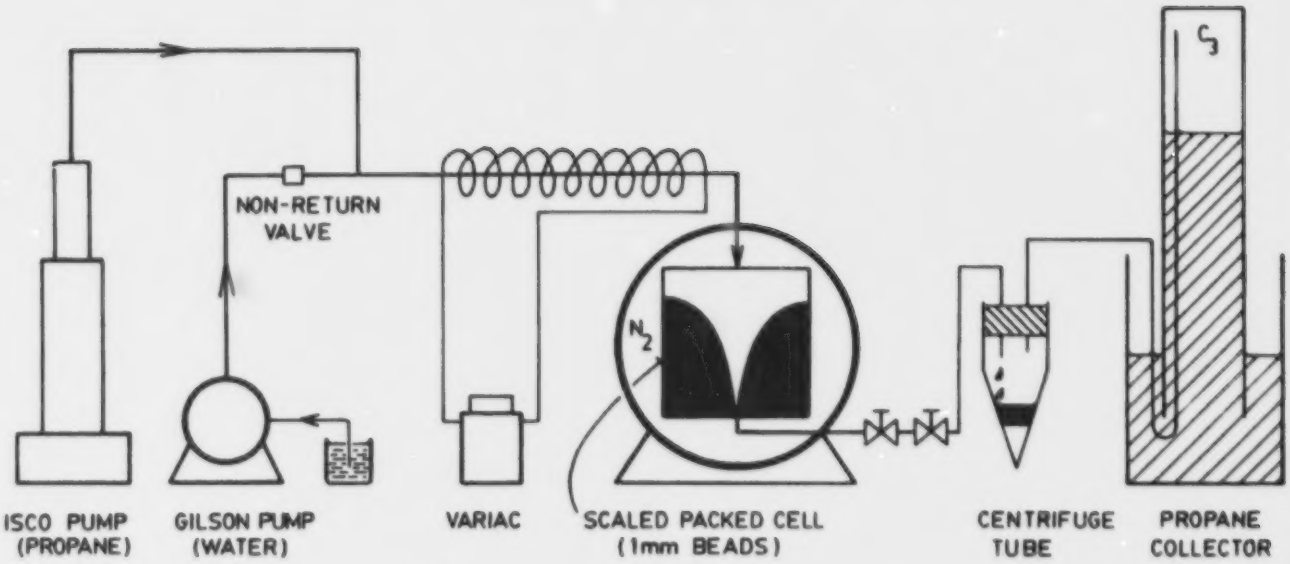


Fig 5.2.1.1: Schematics of the Experimental Set-up for the Injection of Hot Saturated Propane and Hot Water into a Scaled Packed Cell Using Two Pumps.

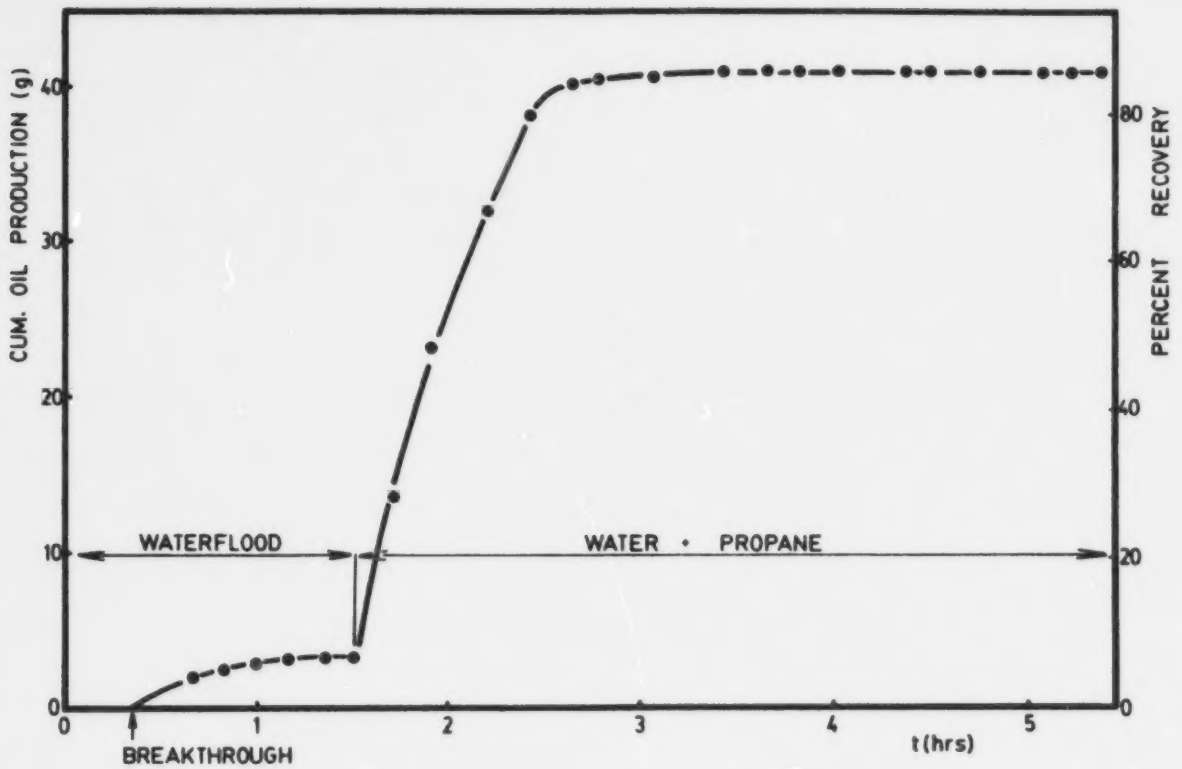


Fig.5.2.1.2: The Effect of Propane Injection on the Cumulative Oil Production from Hot Waterflood. The Average Cell Temperature was about 36°C at Propane Pressure of 150 psi. Two Pump Injection; Oil was Determined Visually from Centrifuged Samples. Data for Run 3.

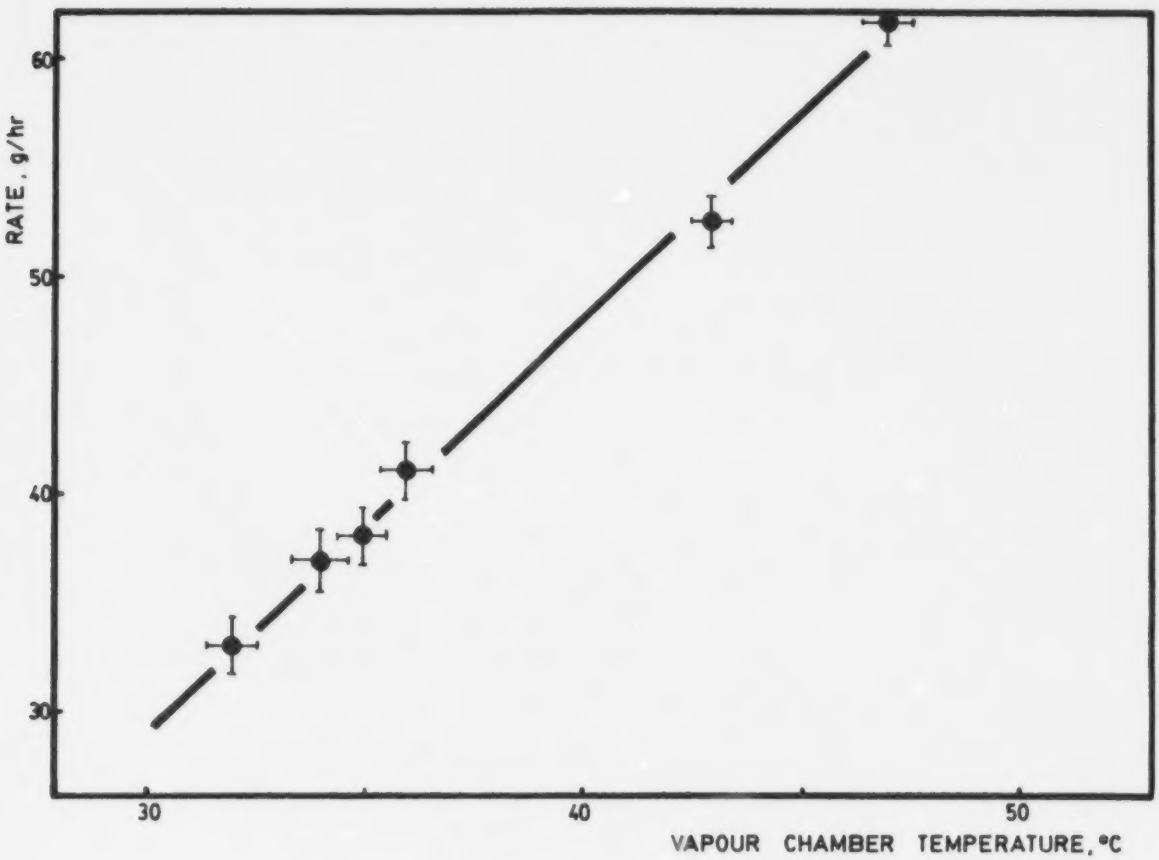


Fig.5.2.1.3: The Rate of Oil Recovery just after the Start of Propane Injection as a Function of Temperature. Data from Table 5.2.1.1.

the cell tends to re-vaporize the propane and recycle it back into the vapour chamber. This is therefore a quite different mechanism from that which is involved in the injection of propane alone. Relatively high production rates are achieved with only a small increase in reservoir temperature. The mechanism and the advantages of the new process will be discussed in a later section.

Propane recoveries during these experiments ranged typically between 85 and 95 percent. Virtually all propane would be recovered in a gas-tight apparatus devoid of leaks and evaporative losses and this is demonstrated by experiments described in the next section.

In the work just described the oil and water in the graduated collection tubes were measured by diluting the total sample with toluene containing a demulsifier, centrifuging and finally measuring the separated phases volumetrically. The presence of large amounts of water/oil emulsions greatly obstructed direct determination of water and oil, even after several periods of centrifuging the sample with an added emulsion breaker. This made it difficult to obtain accurate material balances. The problem was overcome by utilizing the Karl-Fischer method of analysis for water; The experiments which are described in the next section of this report utilize this improved technique and accurate material balances were obtained.

5.2.2 Oil Determined by Karl-Fischer Analysis

Following the experiments described in Section 5.2.1 additional six runs were carried out using the apparatus represented in Fig.5.2.1.1 but with improved analyses and control. They are summarized in Table 5.2.2.1 and the results are plotted individually in Appendix C. The water in produced samples (and therefore by difference the oil) was measured using an automated Karl-Fischer titrator[4]. Mixtures of methanol and isopropanol were used as a solvent. They had to be strong enough to form single-phase homogeneous solutions with the water. The strength of the solvent mixture was adjusted according to the water content. Aliquots of these solutions were then titrated to determine the weight percent of water present. A solvent blank was determined beforehand. The water in the contents of each of the sample tubes which were filled at intervals in the course of the experiment and that in the cell contents after the experiment was determined. The oil was obtained by difference.

Accurate water, oil and propane balances were obtained for the experiments. As an example, in run #5, the total oil determined from our analyses of the contents of 21 sample tubes and of the cell was 49.23 g; this total is in good agreement with the weight of oil put into the cell. This was 49.19 g.

As it can be seen from Table 5.2.2.1 and Figure 5.2.2.1, runs 1,3 and 4 were carried out with the solvent in the vapour phase and agree well with the straight-line relationship plotted in Figure 5.2.1.3 for

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[4]KF Processor 658, Metrohm Ltd, CH-9100 Herisau, Switzerland, using a one-component reagent HYDRANAL-Composite 5 (#34805, made by Fiedel-de Haen AG • D-3016 Seelze 1). The titration according to Karl-Fischer is based on the fact that sulphur dioxide can only be oxidized by iodine in the presence of water, ie. $I_2 + SO_2 + 2\,H_2O \longrightarrow 2\,HI + H_2SO_4$

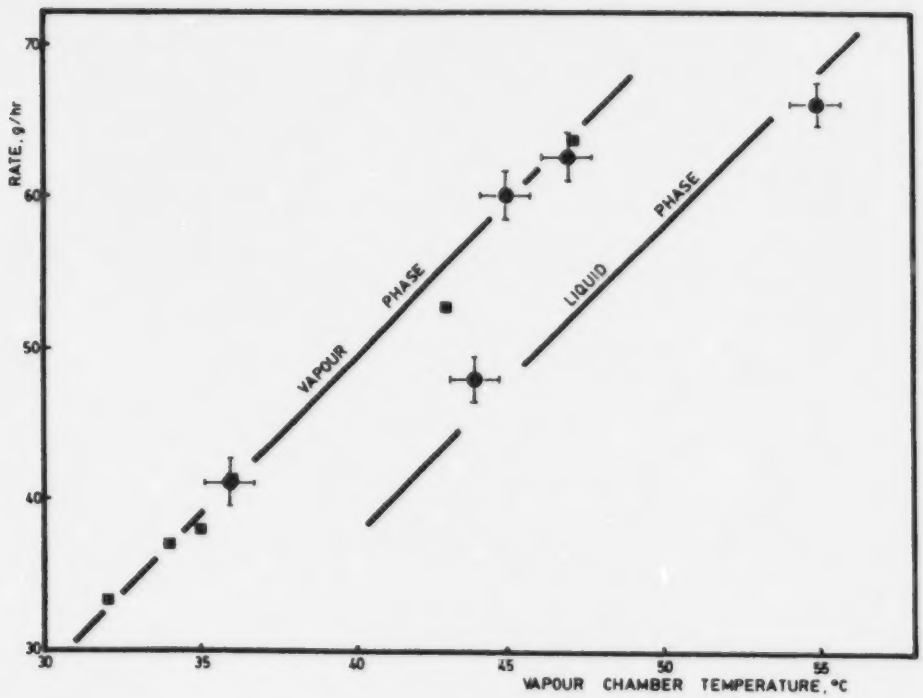

Fig.5.2.2.1.: The Incremental Rate of Oil Recovery due to Propane Injection as a Function of Temperature. Data from Table 5.2.2.1. Squares are points from Fig.5.2.1.3.

TABLE 5.2.2.1
SUMMARY OF SIX RUNS FOR HOT WATER-PROPANE INJECTION

Run No	Average Cell Conditions		Percent Recovery of Oil		Oil Prod.Rate just after propane Injection (g/hr)
	T(°C)	P(psi)	Water	Water/Propane	
1	36	150	21	97	41(v)
2	33	300	20	87	(61(ℓ)[5])
3	45	180	19	89	60(v)
4	47	200	24	90	62.5(v)
5	55	250	32	84	63(ℓ)
6	44	200	24	86	49(ℓ)

the earlier experiments (square points in Fig.5.2.2.1).

On the other hand, runs 5 and 6 were carried out near the propane dew point, but in the liquid phase. Their corresponding rates are therefore shifted to lower values and the rate was about 80 percent of that for the vapour experiments. Since, at the dew point, vapour coexists with liquid and since the experimental conditions (T and P) vary slightly during the experiment, it is not possible to estimate the composition of the propane liquid/vapour mixture (referred to as the 'liquid phase' in Fig.5.2.2.1 and 'ℓ' in Table 5.2.2.1) for runs 5 and 6. The results show that even small amounts of liquid condensate in the propane vapour lower the oil production rate; the presence of liquid propane in the solvent chamber, which is normally filled with pure propane vapour, is therefore undesirable.

Plots in Appendix C indicate that, depending on the length of the experiment, up to 97 percent of the original oil was recovered. Propane recoveries were up to 99 percent, the remaining propane probably stayed dissolved in the oil.

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[5]Poor control, very high propane rate; not plotted in Fig.5.2.2.1.

Appendices B and C also contain water-to-oil and gas-to-oil mass ratios for the respective runs as a function of oil production. The cumulative gas-to-oil ratios vary, typically, between 0.1 to 0.5 g/g for most of the recovery that would be economically attractive (≈ 80%). For recoveries above approximately 80-85% of the OOIP, the G/O ratio rises sharply as a result of both poor sweep efficiency towards the end of the run and very low gravity drainage head for the diluted oil (drainage rate is approximately proportional to the square root of the head). For this reason, most experiments had been stopped at about 85 to 90 percent recovery of oil.

The gas-to-oil ratio and water-to-oil ratio for the same experiment shown in Fig.5.2.1.2 (ie. run 3) are plotted in Fig.5.2.2.2. In this experiment the total water injected was 8 times the volume of oil produced for a recovery of 80 percent of OOIP. The ratio of the cumulative injected propane to the cumulative produced oil was about 0.4 for the same recovery; 99% of the injected propane was recovered.

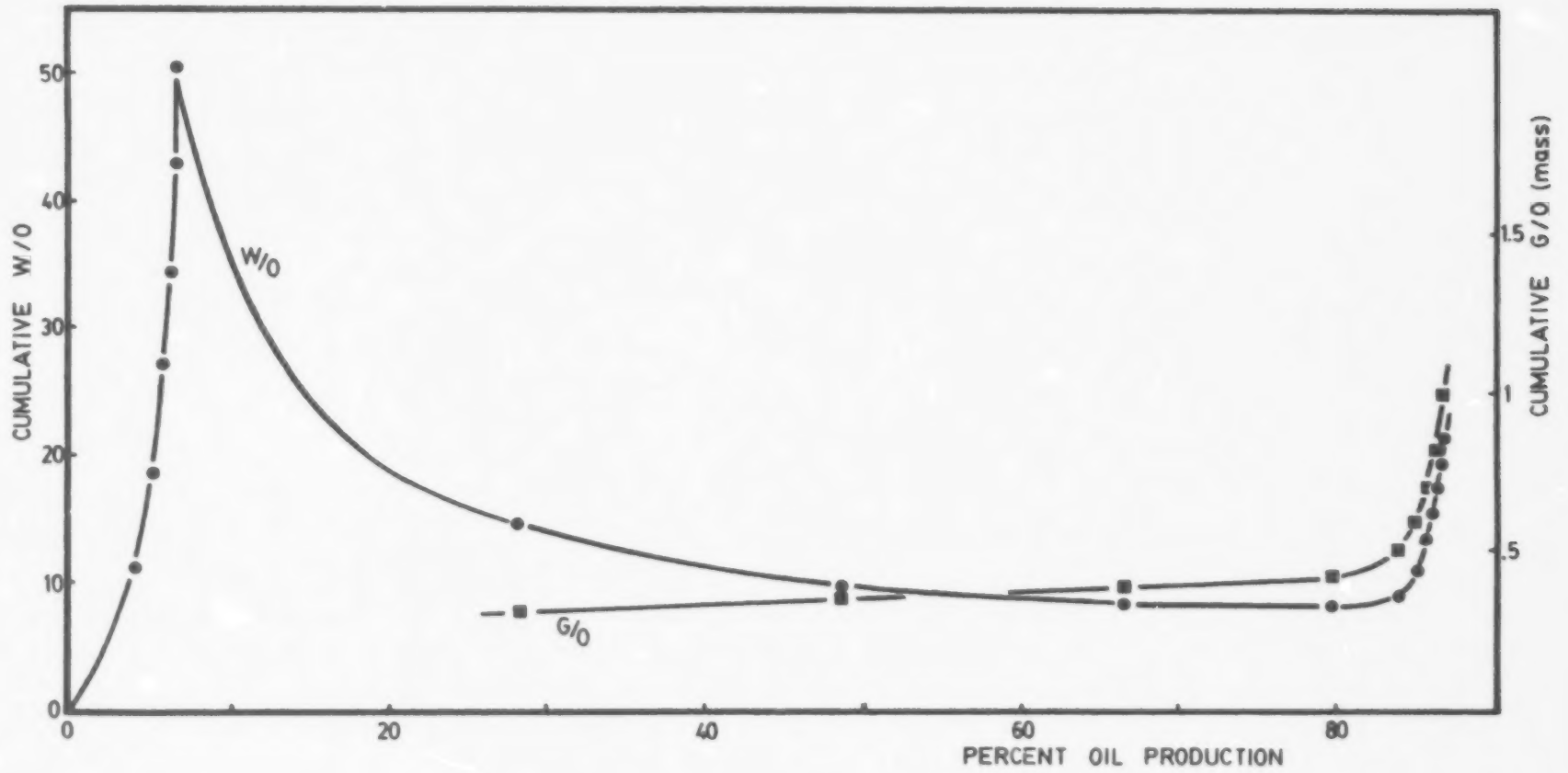

Fig.5.2.2.2.: Cumulative water-to-oil and gas-to-oil ratios as a function of oil Production for Run 3 in Table 5.2.1.1.

5.2.3 Scaling of Production Rates for the Packed Cell

The initial production rates in Tables 5.2.1.1 and 5.2.2.1 can be scaled to predict the field performance of the new process. Run 4 in Table 5.2.1.1 will be used as an example. It was carried out at 47°C and the initial production rate of 63.8 g/hr was obtained in the packed cell 7 cm high and 2.54 cm deep. Assuming the reservoir height of 12.9 m (Section 4.1.2), using the time scaling factor defined by Eq.(4.1.2.2) and taking $\rho_{oil} \approx 1\ g/cm^3$, the model production per unit depth of cell is:

$$63.8\ \frac{cm_M^3}{hr_M} \cdot \frac{1}{2.54\ cm_M} = 25.12\ \frac{cm_M^2}{hr_M} = 0.002512\ \frac{m_M^2}{hr_M}$$

Substituting for one model hour from Eq.(4.1.2.2) and considering that 0.07 m_M is equivalent to 12.9 m_F, then the equivalent field production per 1 m of well is:

$$0.002512\ \frac{m_M^2}{4.33\ yrs_F} \cdot \left(\frac{12.9}{0.07}\right)^2 \frac{m_F^2}{m_M^2} = 19.70\ \frac{m_F^2}{yr_F}$$

$$= .054\ \frac{m_F^2}{d_f}$$

$$\text{or field production per foot of well} = .0165\ m_F^3/(ft \cdot d_F)$$

$$= .1035\ bbl/(ft \cdot d_F)$$

Using this process in conjunction with a 457 m (1500 ft) horizontal well drilled through a 12.9 m thick pay zone would therefore recover about 155 bbl of oil per day. However, it should be pointed out that the preliminary experimental work which forms the basis for this estimate has not been optimised for the best performance.

5.3 Mechanism of the Vapex Process

The mechanism of the new process is illustrated schematically in Fig.5.3.1. The essential features of this process are as follows:

Following hot water/propane injection into the reservoir, an initially vertical solvent vapour chamber is formed between the injector and the producer. Within this chamber the solvent is recycled by evaporation from the diluted draining oil which is heated by the hot water. The warm propane vapour then rises countercurrently to the draining water and increases its temperature as it comes in contact with hotter water near the top of the reservoir. It then moves to the far reaches of the chamber where it dissolves in the cold undiluted reservoir oil.

As a result, the vapour chamber spreads laterally. The oil-solvent interface[6] becomes stabilized by gravity and acquires its characteristic S-shape for each half of the chamber. The drainage is controlled by molecular diffusion of solvent vapour into the bitumen.

The function of the hot water is therefore twofold : it heats up the reservoir matrix lowering the oil viscosity in the process and also releases propane vapour from warm draining oil for re-use at the top of the vapour chamber.

Although heat is used in our process, the quantity of heat is relatively small compared to that for the steam process and, because the temperatures are low, the heat losses are greatly reduced, allowing economic operations in much thinner reservoirs.

The lateral spread of the vapour chamber is made possible by the combination of continuous transport of heat to the perimeter of the

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[6]It consists of a very thin band (referred to as the convection or diffusion boundary layer) in which the diluted oil is transported by gravity drainage [6].

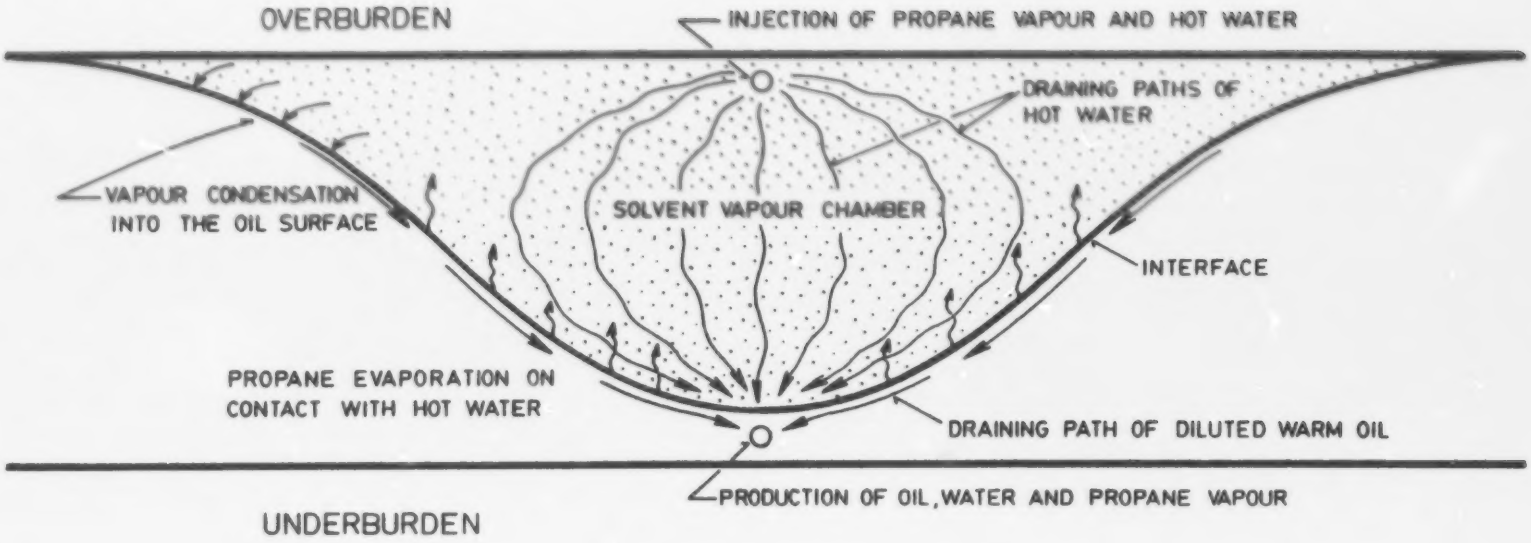
OVERBURDEN
INJECTION OF PROPANE VAPOUR AND HOT WATER
DRAINING PATHS OF HOT WATER
VAPOUR CONDENSATION INTO THE OIL SURFACE
SOLVENT VAPOUR CHAMBER
INTERFACE
PROPANE EVAPORATION ON CONTACT WITH HOT WATER
DRAINING PATH OF DILUTED WARM OIL
PRODUCTION OF OIL, WATER AND PROPANE VAPOUR
UNDERBURDEN

FIG. 5.3.1. Mechanism of the VAPEX Process. (Dots represent vapour)

chamber through the mechanism of solvent evaporation and condensation with the continuous removal of diluted oil by gravity drainage. The function of the solvent (eg.propane) is therefore also twofold: it dilutes the oil in the far reaches of the solvent chamber and it distributes the heat laterally away from the plane of injector and producer. As a result, a large expanse of reservoir can be drained from a pair of injection and production wells.

The process of boiling off some of the solvent from the diluted draining oil sets up a small pressure gradient in the vapour phase which is sufficient to drive the re-vapourized solvent towards the cold, undiluted oil at the perimeter of the vapour chamber. Some of the solvent eventually leaves the vapour chamber as solution gas and free gas.

In order to maximize the solvent vapour contact with the reservoir, and therefore the rate with which the oil can be recovered, both wells should be drilled horizontally, with the injector located above the producer. We envisage a commercial process that would involve a battery of horizontal wells spaced at intervals determined by the extent of the lateral spread of the solvent chambers.

5.4 Potential Improvements

In Section 5.2.3 it was shown that drainage rates of the order of 0.1 bbl/(d•ft) could be anticipated in the field. Although somewhat lower than rates for steam-assisted gravity drainage, this value seems high enough for the process to be economically viable under some circumstances. It should be appreciated that, up until now, there has been no attempt for optimization in our experiments. There are opportunities. For example, higher temperatures than 47°C should give higher rates and more attractive extrapolations to field conditions. It is also possible that improved techniques of operation may be developed. For example, pressure cycling could be beneficial.

Another possibility is to optimize the process by locating the injection well lower in the reservoir - an attractive configuration might be to place the injection well at about one-third of the height of the reservoir. This would produce a more favourable temperature distribution with only the lower part of the reservoir heated and would allow considerable refluxing of the extraction vapour. There would be a larger hold up of propane within the reservoir but a lower concentration in the produced fluids and a lower requirement for propane recycling.

This approach, because it would facilitate the establishment of communication (very hot water, even steam could be used for the initial communication phase), would extend the application of the technique to more viscous oils such as the tars in Grosmont, Cold Lake and Athabasca. The application to the Grosmont carbonate reservoir could be attractive because, even though its permeability may be high, its low porosity tends to make the heat requirements for conventional thermal processes excessive. With the propane/hot water technique, the high heat capacity of this low-porosity reservoir per unit quantity of contained oil is of lesser importance.

6. Conclusions

A new vapour extraction process (the VAPEX Process) that allows economic production of oil from heavy oil reservoirs is proposed. Its fundamental characteristics are:

1. A mixture of hot water and a low boiling vapourized solvent such as propane is injected into the reservoir.
2. The injected fluids must contain sufficient heat to warm the reservoir to a temperature typically in the range of 40 to 70°C.
3. A solvent vapour chamber is formed which spreads laterally from the vertical plane of the injector and producer.
4. As the diluted bitumen drains by gravity towards the producer, it interacts with the hot water and a part of the dissolved propane (or other solvent) is boiled off into the solvent chamber where it propagates further lateral growth of the chamber. The solvent vapour thus acts as a heat carrier and causes warming at the boundary of the chamber.
5. Experimental evidence shows that the injection of propane vapour with hot water results in high oil recovery. This is far higher than could be obtained with hot water alone.
6. The propane requirements in the experiments described were of the order of 0.5 kg per kg of oil recovered or less for an oil recovery of 80%. Nearly all of the injected propane was recovered with the oil. It is anticipated that, with the development of the process, operation with a much lower recycle of propane will be achieved.
7. Advantages of this new process are:
    - the solvent is inexpensive and can be recovered and recycled
    - there are much smaller heat losses involved in the process than with conventional steaming

- the process is suited for thin reservoirs as well as thicker ones.

8. Another area where the new process may have potential advantages is in the recovery of heavy oils and bitumen from low porosity but good permeability reservoirs such as the Grosmont Karsts in Alberta.

LIST OF SYMBOLS

A	flow face area, m^2
APU	arbitrary planimeter units, dimensionless
b	Hele-Shaw cell plate spacing, μm
d	diameter (of packing beads), mm, or day
F	field
g	acceleration due to gravity, m d^{-2} (Eq.2.1)
H	reservoir (or cell) height, m
k	absolute permeability, darcy
ℓ	liquid phase
M	model
P	pressure, atm
P_c	critical pressure, psi
R	reservoir
ΔS	$S_{oi} - S_{or}$, change in oil saturation, fraction
t	time, s
T_c	critical temperature, ^oC
T_R	reservoir temperature
T_S	steam temperature
v	vapour phase
V	bulk volume, m^3
Q_b	volumetric flow rate of bitumen, m^3/s
μ	absolute viscosity, mPa.s
ϕ	porosity, percent

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We also wish to acknowledge the valuable contribution of the late Dr. Mohammed M. Moussa who supervised the preliminary work reported in Section 3.2.

Appendices

Figure A1 of Appendix A depicts liquid propane viscosity as a function of temperature. This relationship is approximately linear within the narrow temperature range of 20 to 90°C and can be represented by the regression equation,

$$\mu = - 0.000953\ T + 0.126498 \qquad (A1)$$

where $20^{\circ}C \leq T \leq 90^{\circ}C$.

The critical temperature for pure propane is 96.8°C which results in a sharp curvature in this region.

Figure A2 shows the density of the Tangleflags North heavy oil as a function of temperature.

Figure A3 is a plot of vapour-liquid equilibrium for pure propane and for the CP grade propane used. This plot was very useful in determining the initial pressure to which the modified ISCO backpressure pump had to be set to prevent sudden propane breakthrough. As may be seen from Table 3.3.6.1, the rate measurements were carried out to within 6.8°C of the critical temperature.

Figure A4 shows the viscosity-temperature relationship for the Tangleflags North Heavy Oil [4] which was used in the experiments.

Figures A5a to A11b refer to hot propane injection into the packed cell (Section 4.1.3) and list the oil production rates and gas-oil ratios. These results are summarized in Table 4.2.1 and Figures 4.2.1 to 4.2.3.

Appendix B contains data for the individual runs which are summarized in the Table 5.2.1.1. Plots of experiments summarized in Table 5.2.2.1. comprise Appendix C.

APPENDIX A

PHYSICAL DATA AND HELE-SHAW EXPERIMENTS

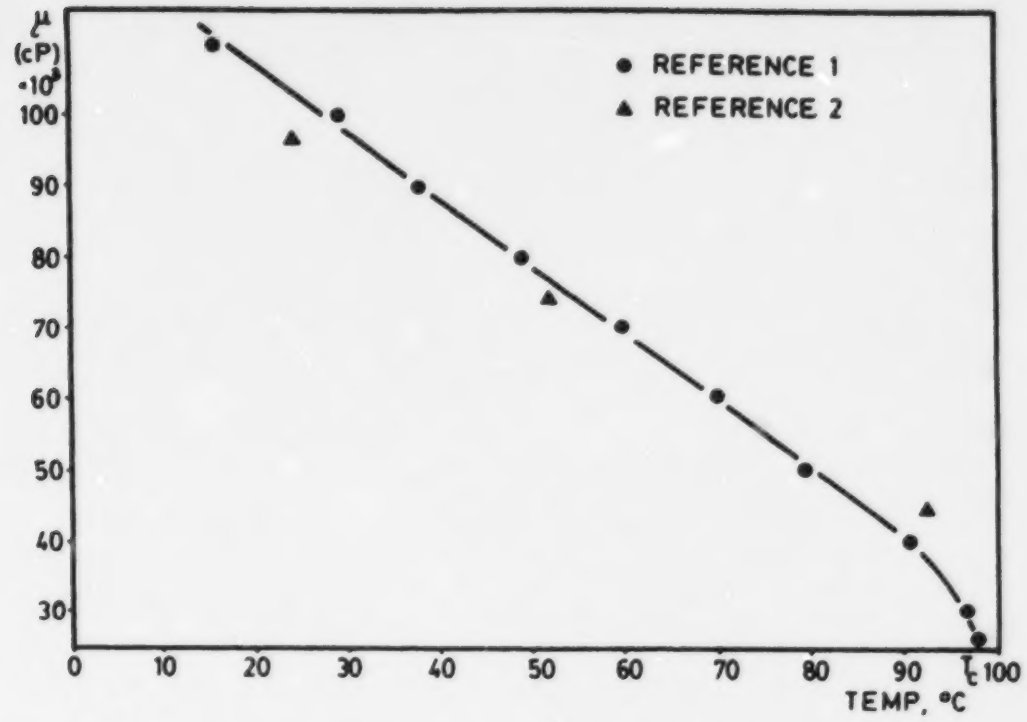

FIGURE A1: LIQUID PROPANE VISCOSITY

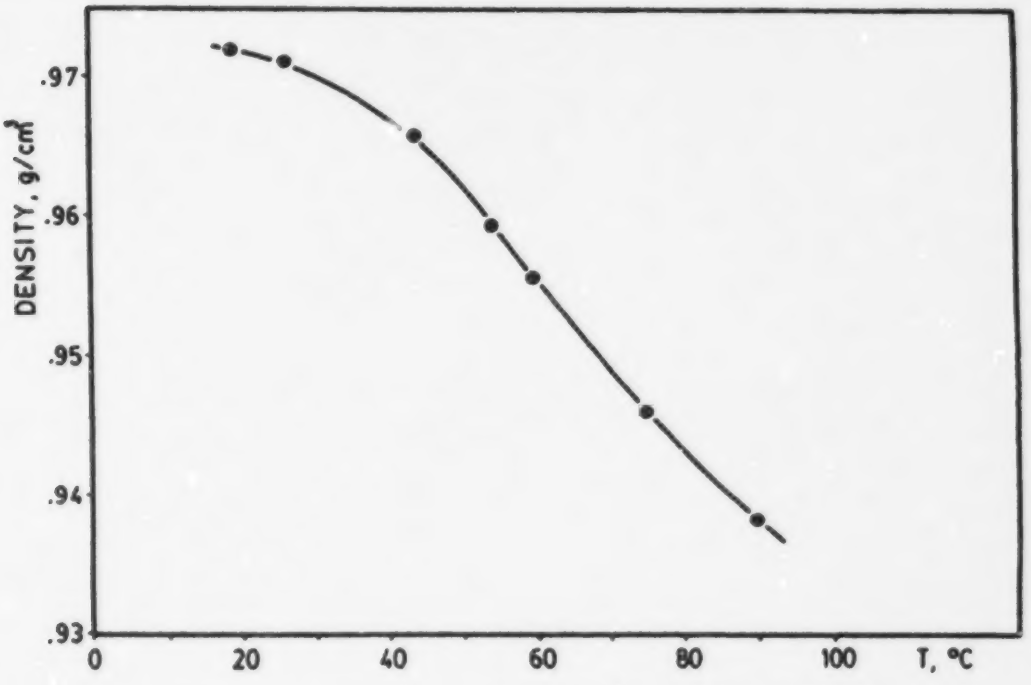

FIGURE A2: DENSITY OF TANGLEFLAGS NORTH HEAVY OIL

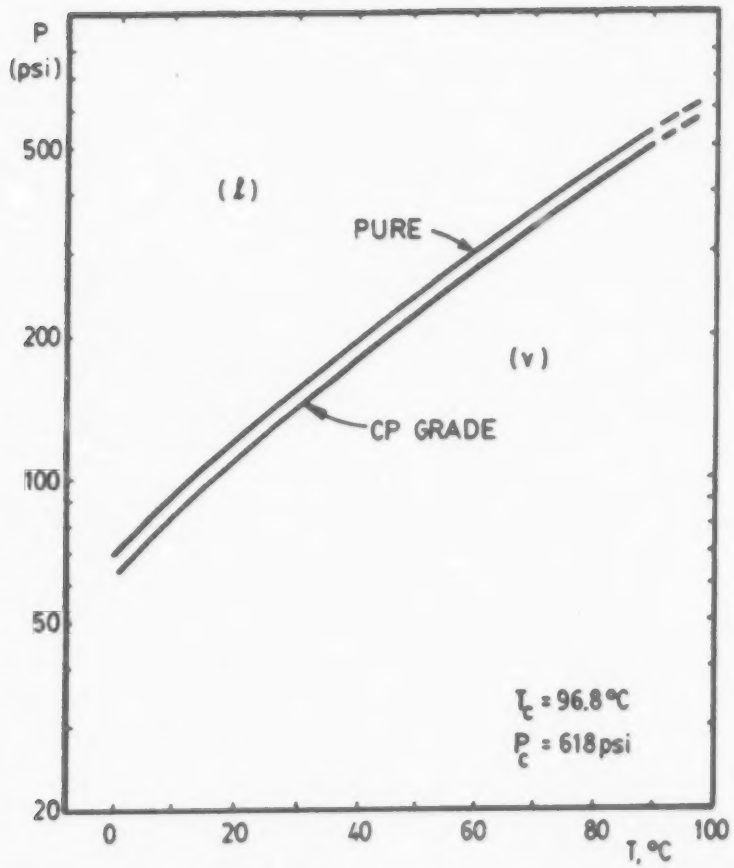

FIGURE A3: Vapour Pressure Curves for Pure and CP Grade Propane

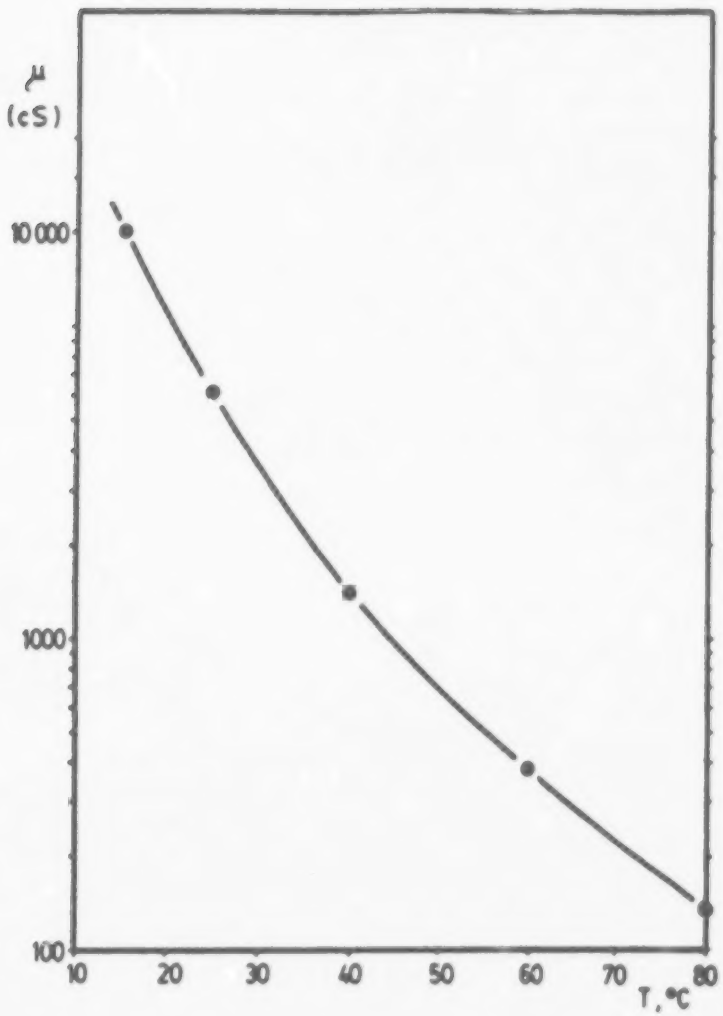

FIGURE A4: Viscosity of Tangleflags North [4].

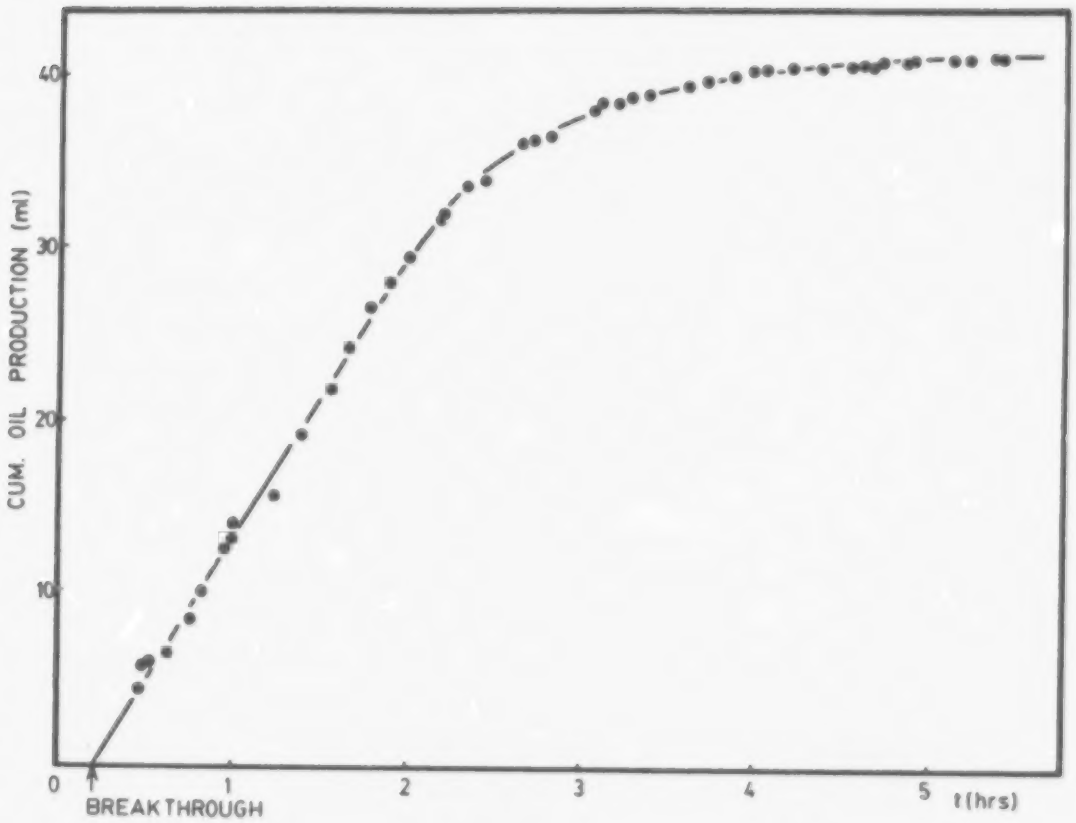

FIGURE A5a: Rate of Oil Production at 80°C for Hot Propane Injection into the Scaled Packed Cell. Refers to Fig. 3.2.1.

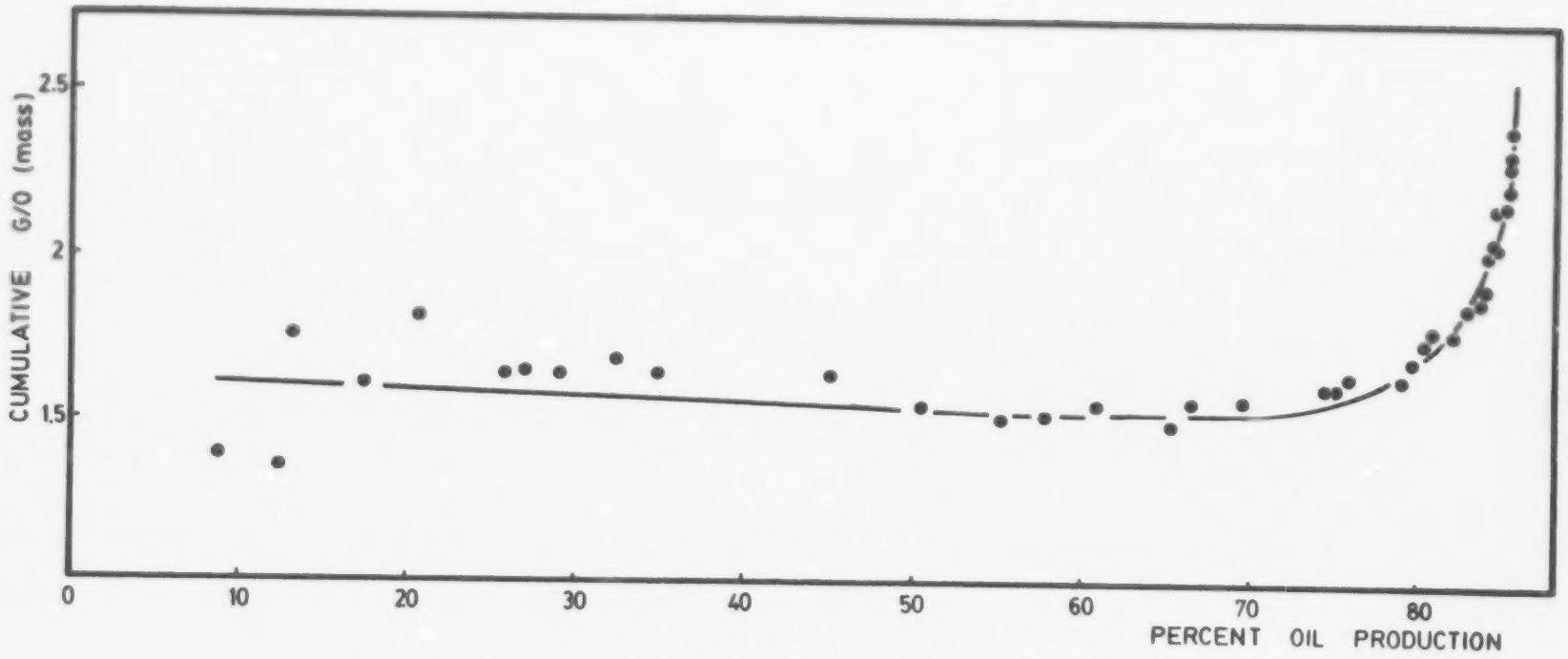

FIGURE A5b: Cumulative Gas/Oil Ratios as a Function of Oil Production at 80°C for Hot Propane Injection into the Scaled Packed Cell. Refers to Fig. 3.2.2.

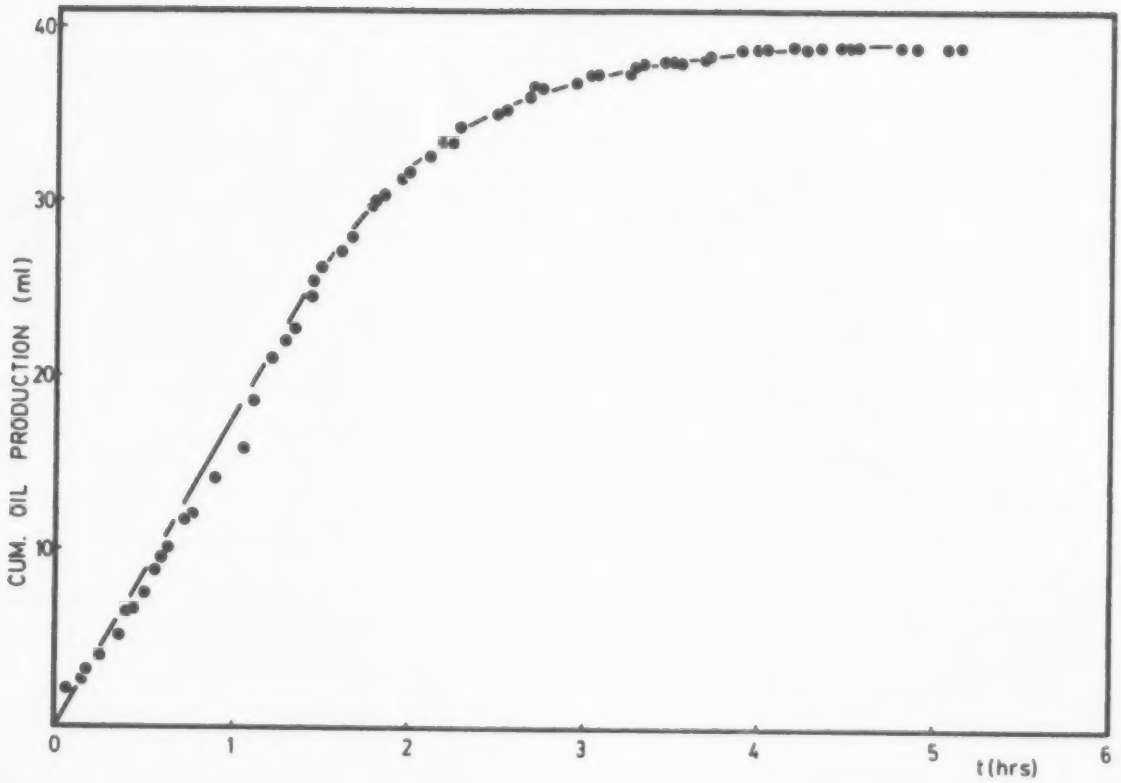

FIGURE A6a: Rate of Oil Production at 70°C for Hot Propane Injection into the Scaled Packed Cell. Refers to Fig. 3.2.1.

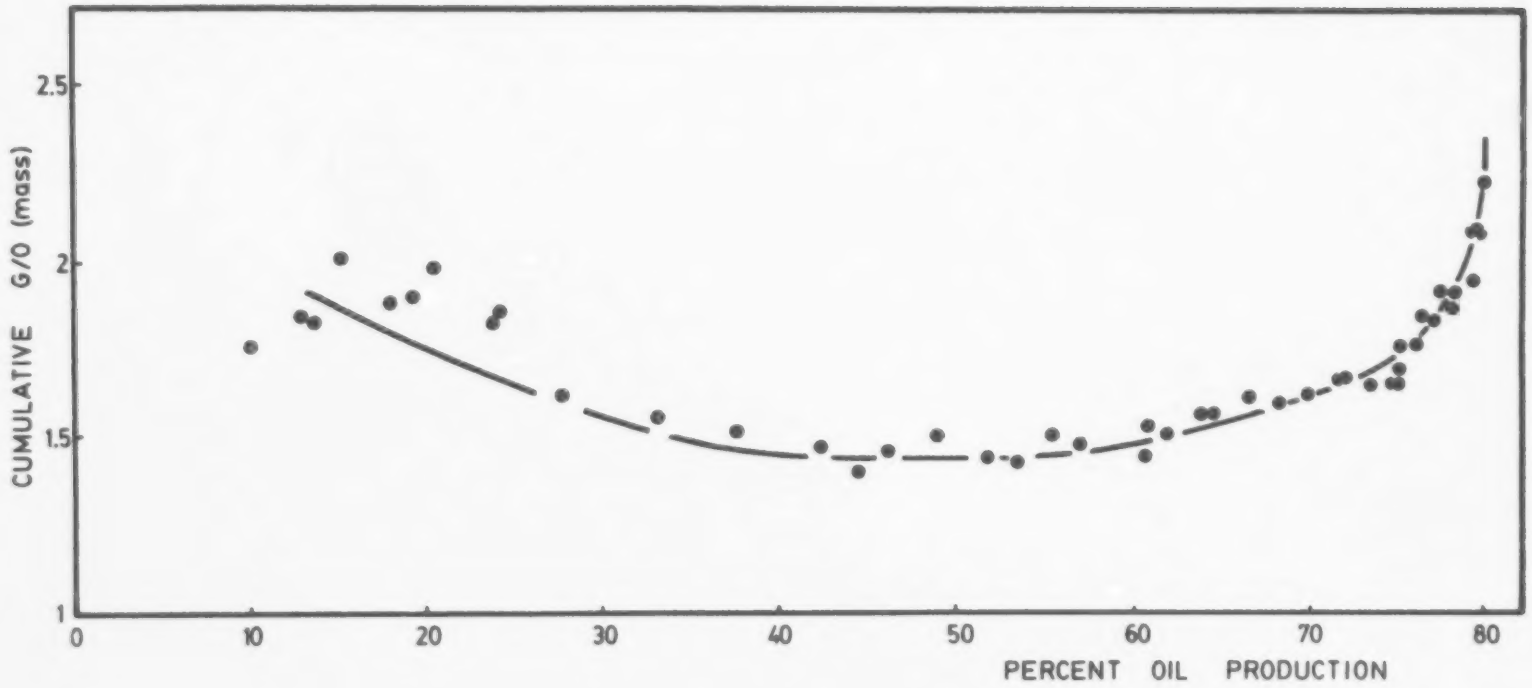

FIGURE A6b: Cumulative Gas/Oil Ratio as a Function of Oil Production at 70°C for Hot Propane Injection into the Scaled Packed Cell. Refers to Fig. 3.2.2.

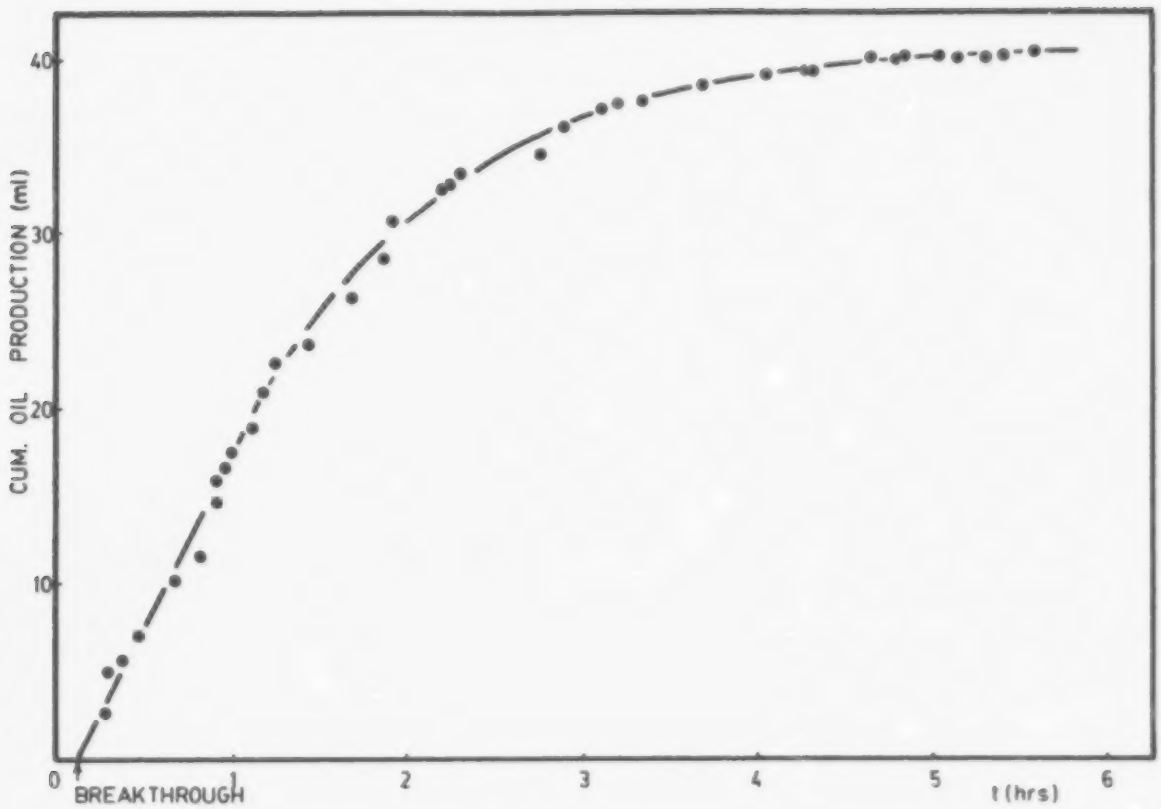

FIGURE A7a: Rate of Oil Production at 67°C for a Hot Propane Injection into the Scaled Packed Cell. Refers to Fig. 3.2.1.

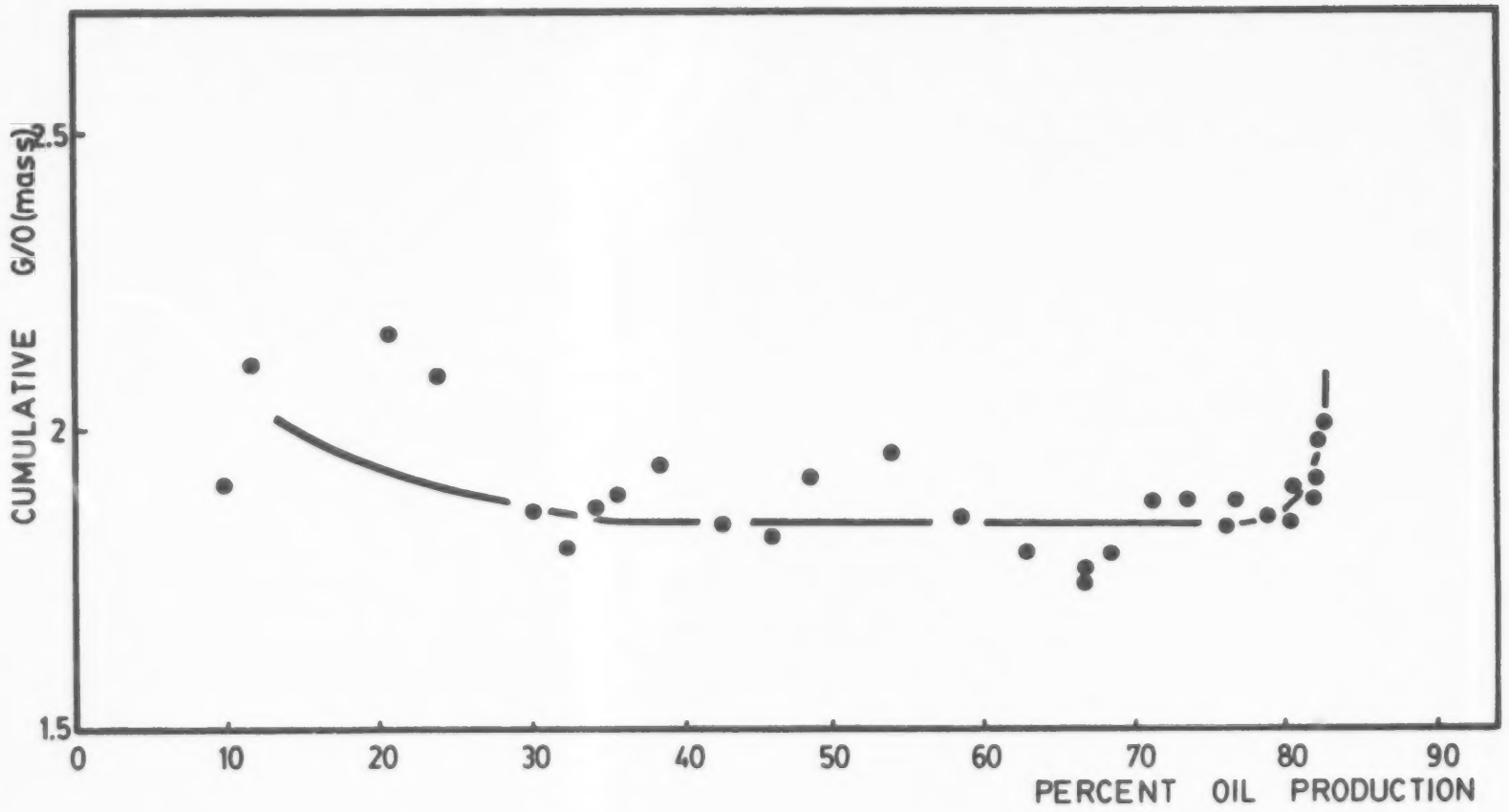

FIGURE A7b: Cumulative Gas/Oil Ratio as a Function of Oil Production at 67°C for Hot Propane Injection into the Scaled Packed Cell. Refers to Fig. 3.2.2.

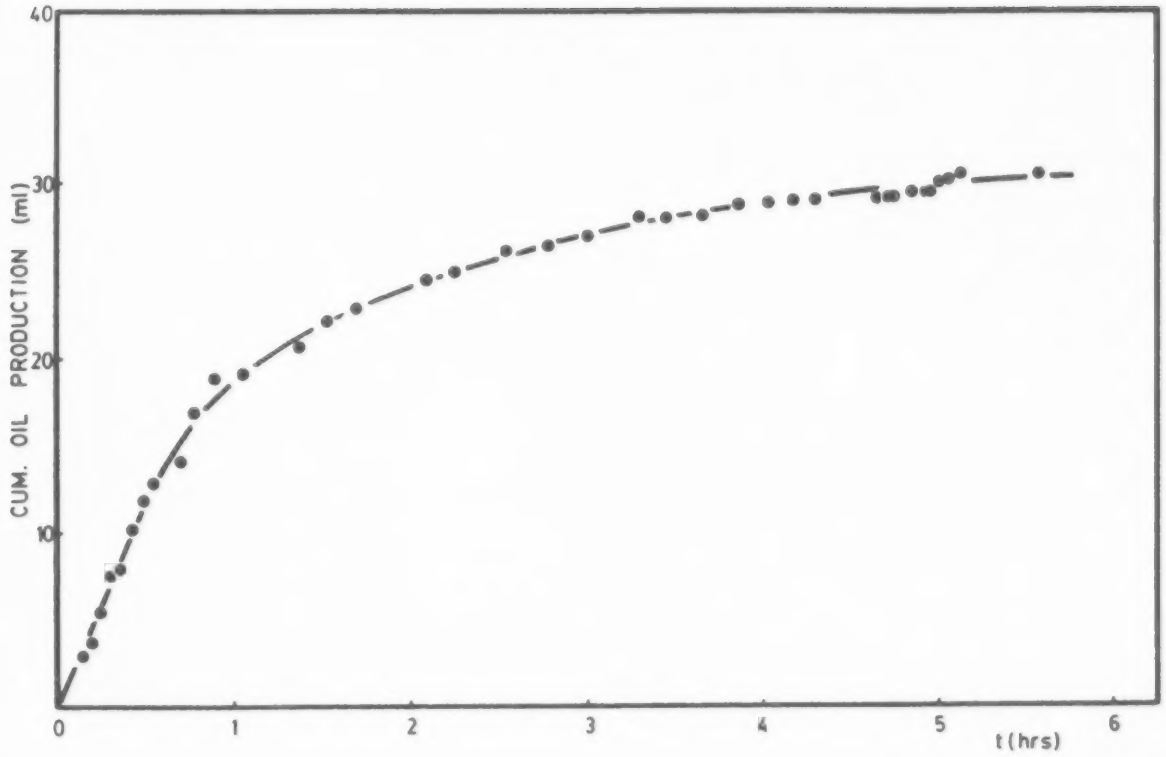

FIGURE A8a: Rate of Oil Production at 50°C for Hot Propane Injection into the Scaled Packed Cell. Refers to Fig. 3.2.1.

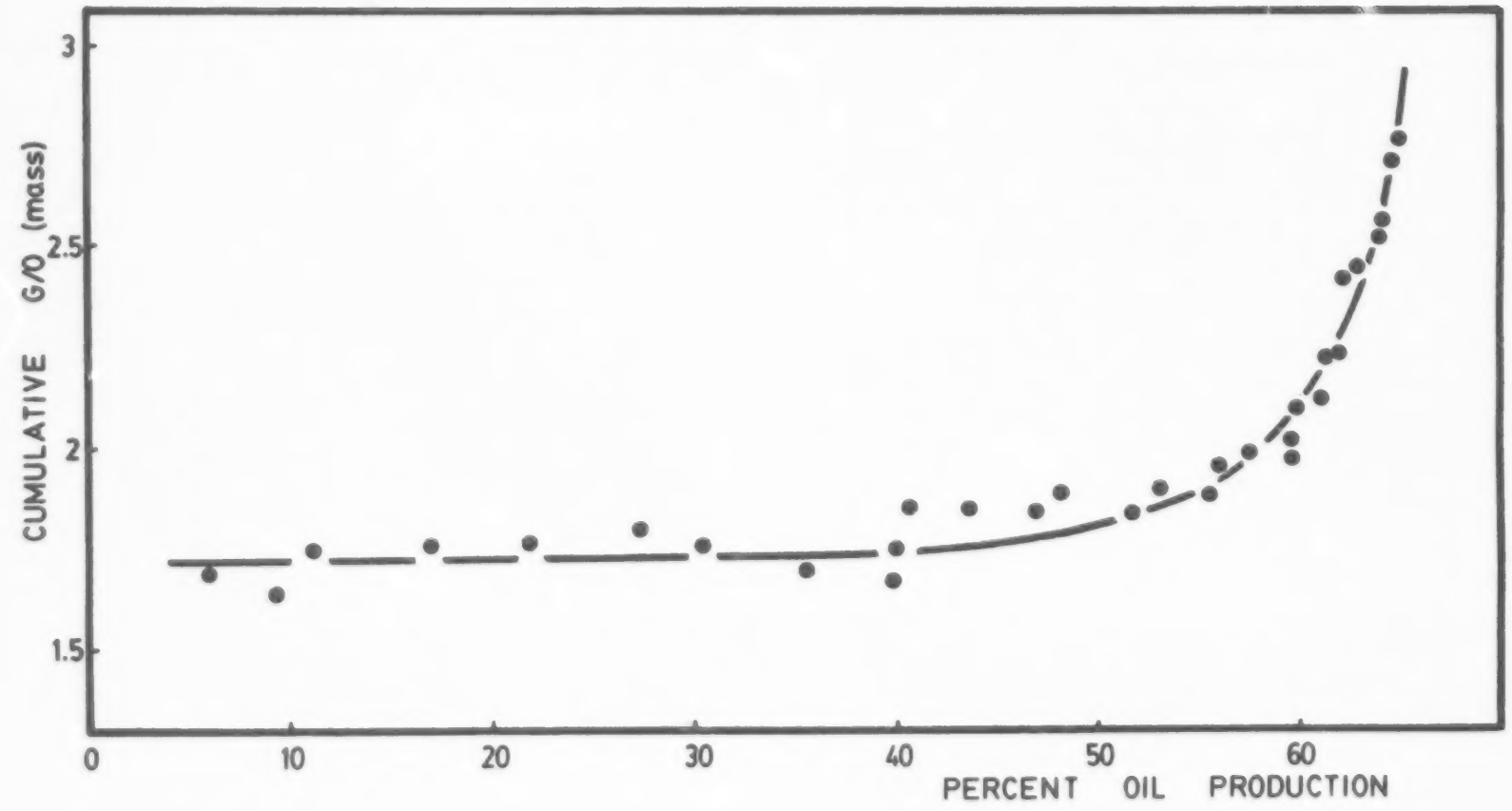

FIGURE A8b: Cumulative Gas/Oil Ratio as a Function of Oil Production at 50°C for Hot Propane Injection into the Scaled Packed Cell. Refers to Fig. 3.2.2.

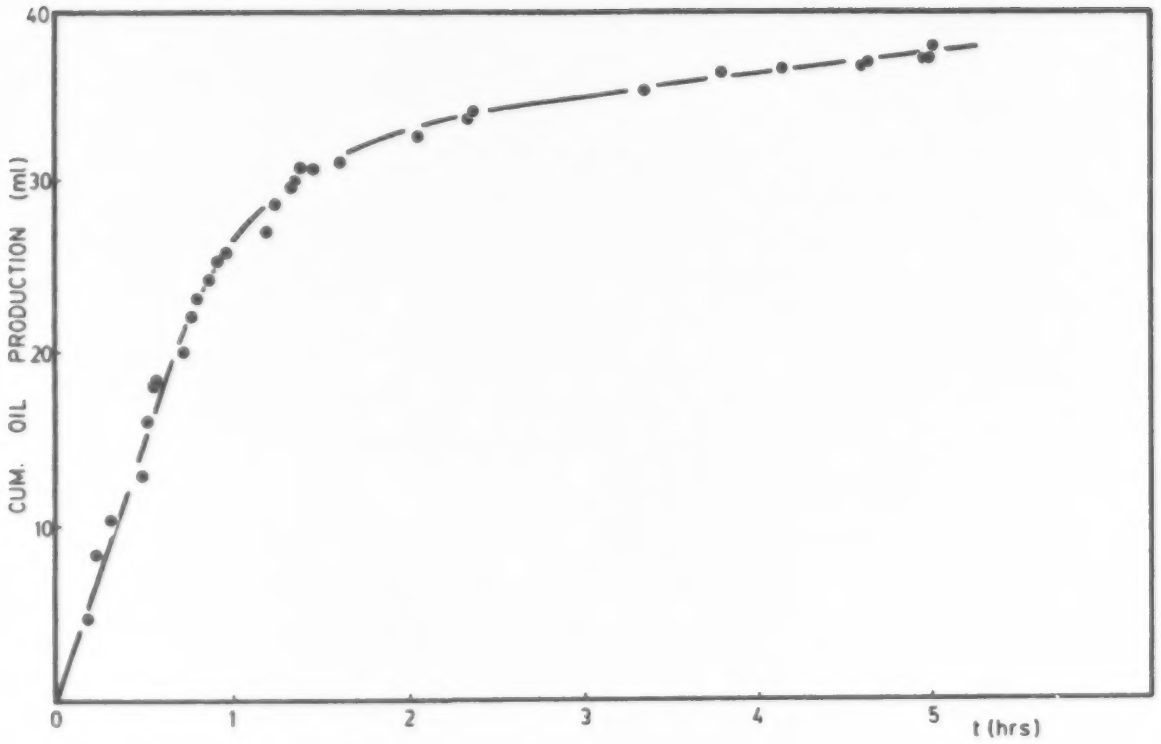

FIGURE A9a: Rate of Oil Production at 40°C for Hot Propane Injection into the Scaled Packed Cell. Refers to Fig. 3.2.1.

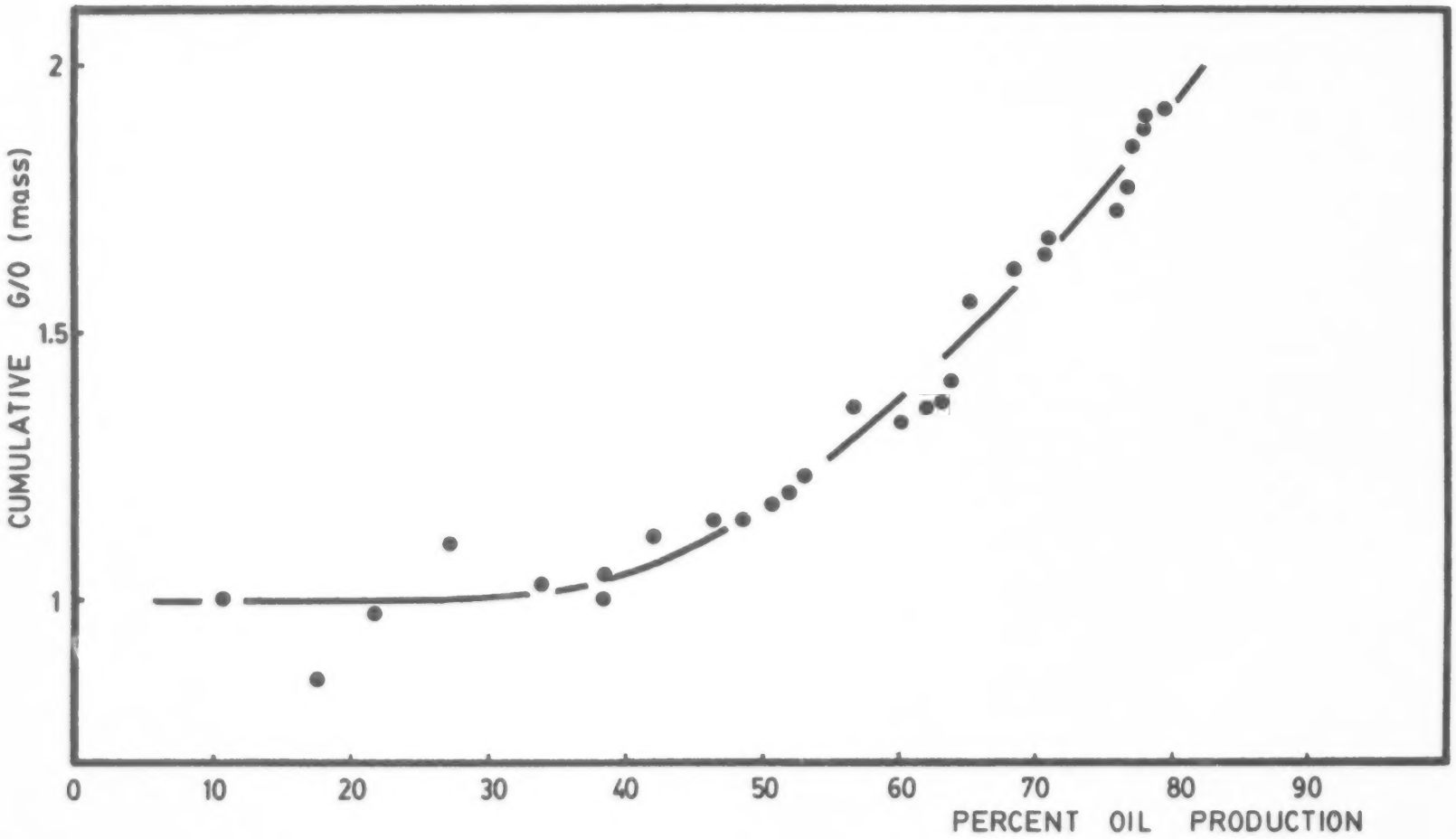

FIGURE A9b: Cumulative Gas/Oil Ratio as a Function of Oil Production at 40°C for Hot Propane Injection into the Scaled Packed Cell. Refers to Fig. 3.2.2.

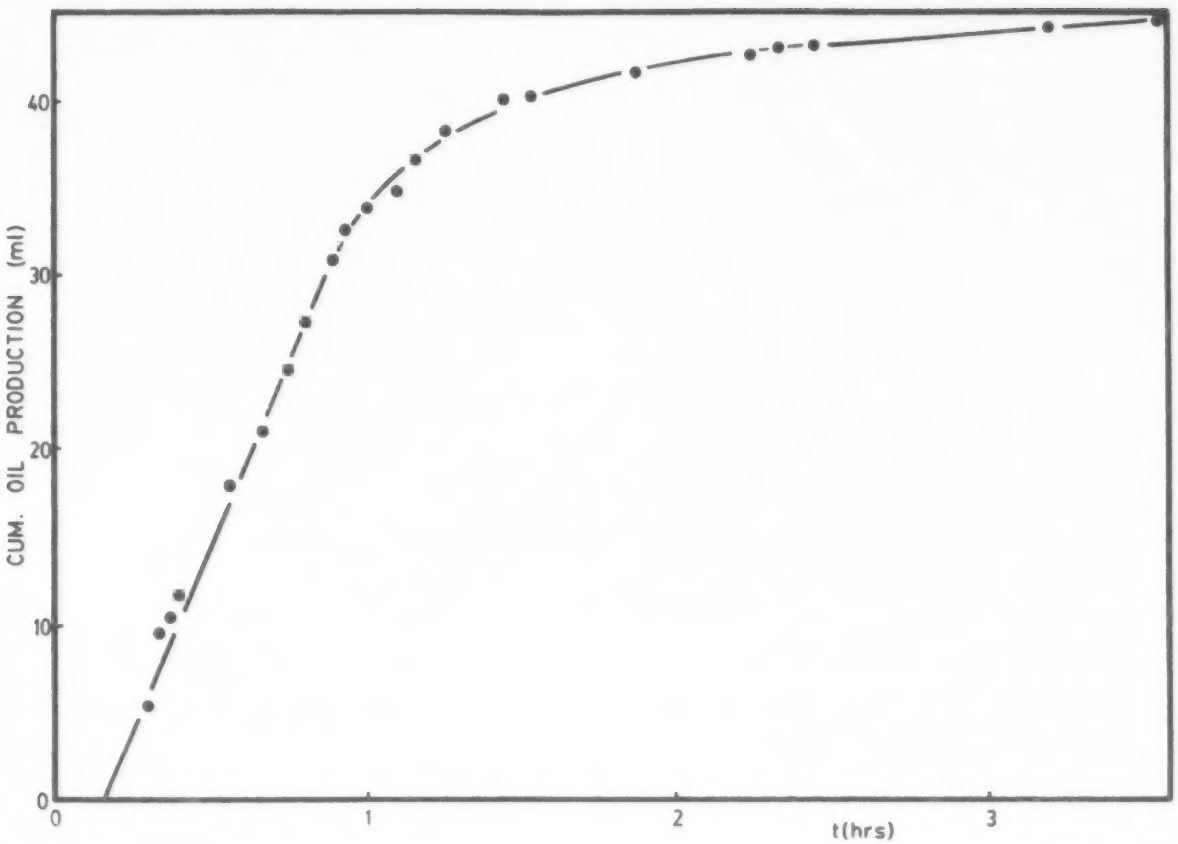

FIGURE A10a: Rate of Oil Production at 27°C for Hot Propane Injection into the Scaled Packed Cell. Refers to Fig. 3.2.1.

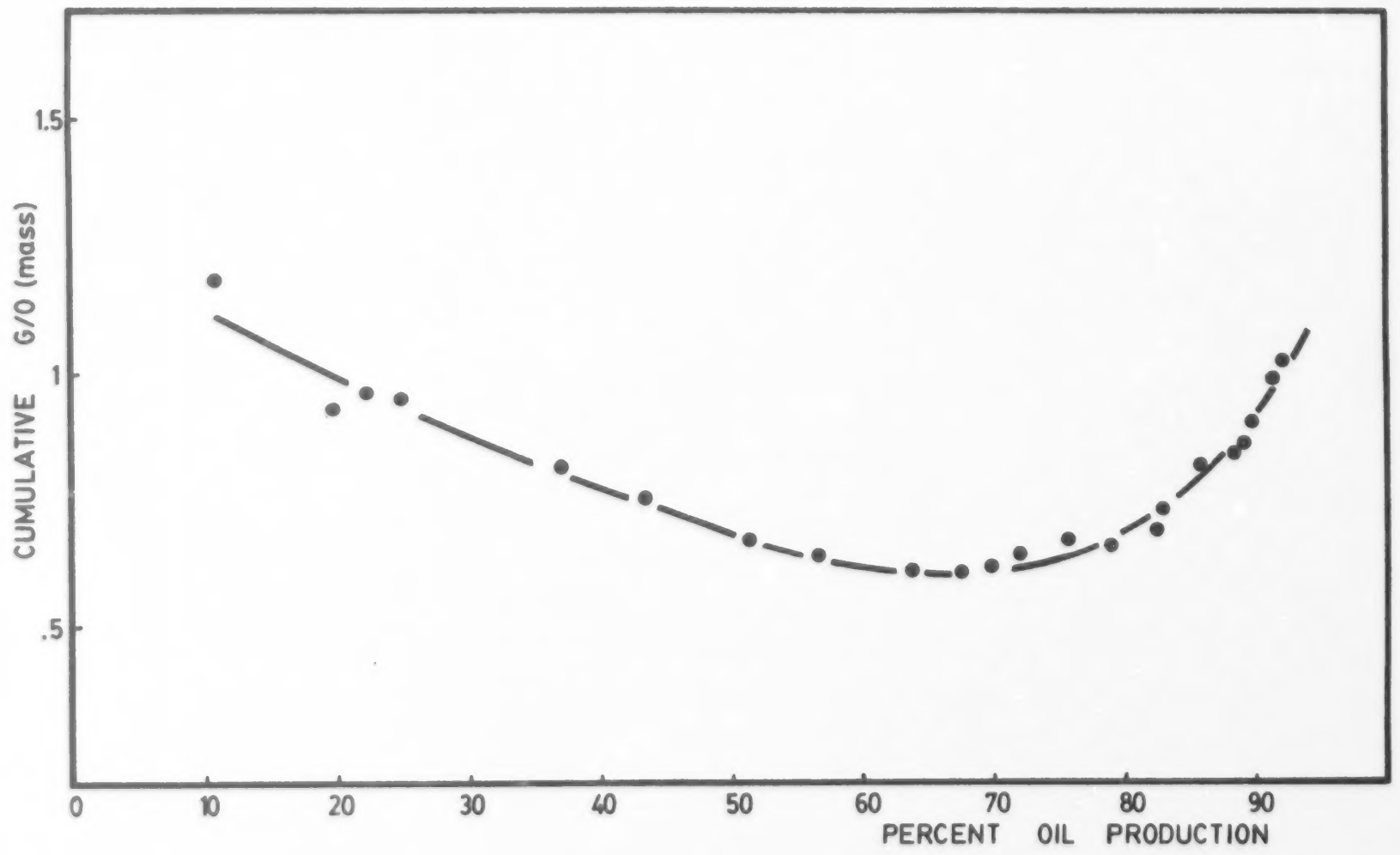

FIGURE A10b: Cumulative Gas/Oil Ratios as a Function of Oil Production at 27°C for Hot Propane Injection into the Scaled Packed Cell. Refers to 3.2.2.

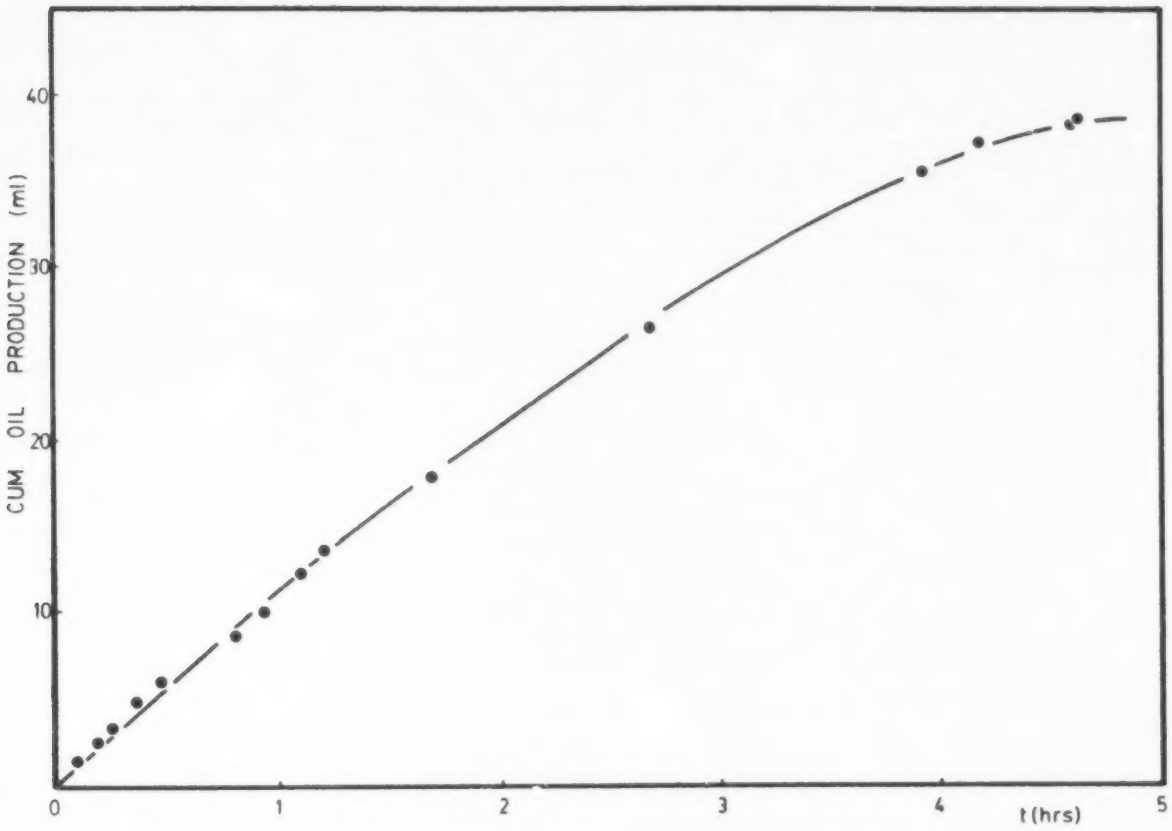

FIGURE Alla: Rate of Oil Production at 20°C for Hot Propane Injection into the Scaled Packed Cell. Refers to Fig. 3.2.1.

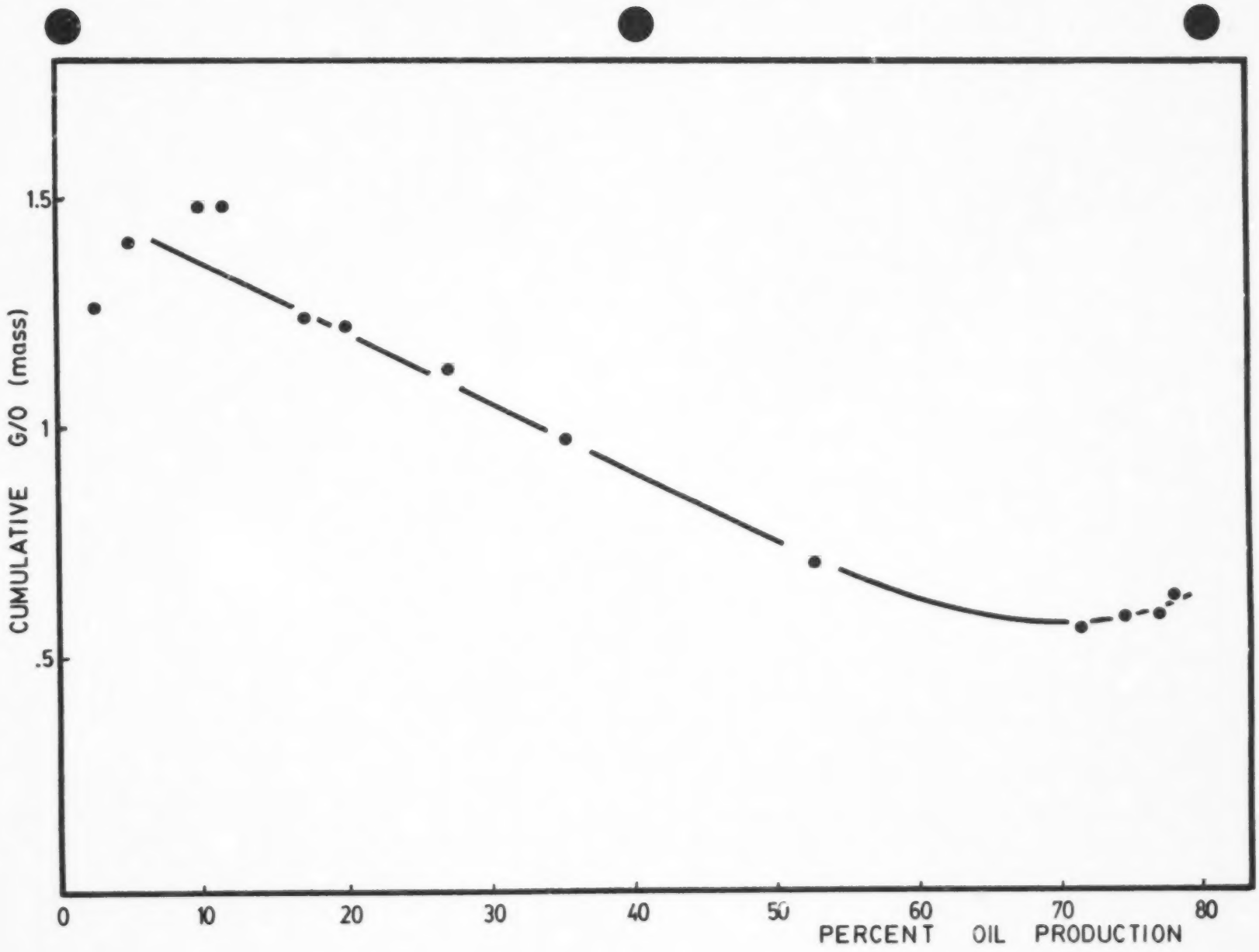

FIGURE A11b: Cumulative Gas/Oil Ratio as a Function of Oil Production at 20°C for Hot Propane Injection into the Scaled Packed Cell. Refers to Fig. 3.2.2.

APPENDIX B

PRELIMINARY PACKED CELL EXPERIMENTS

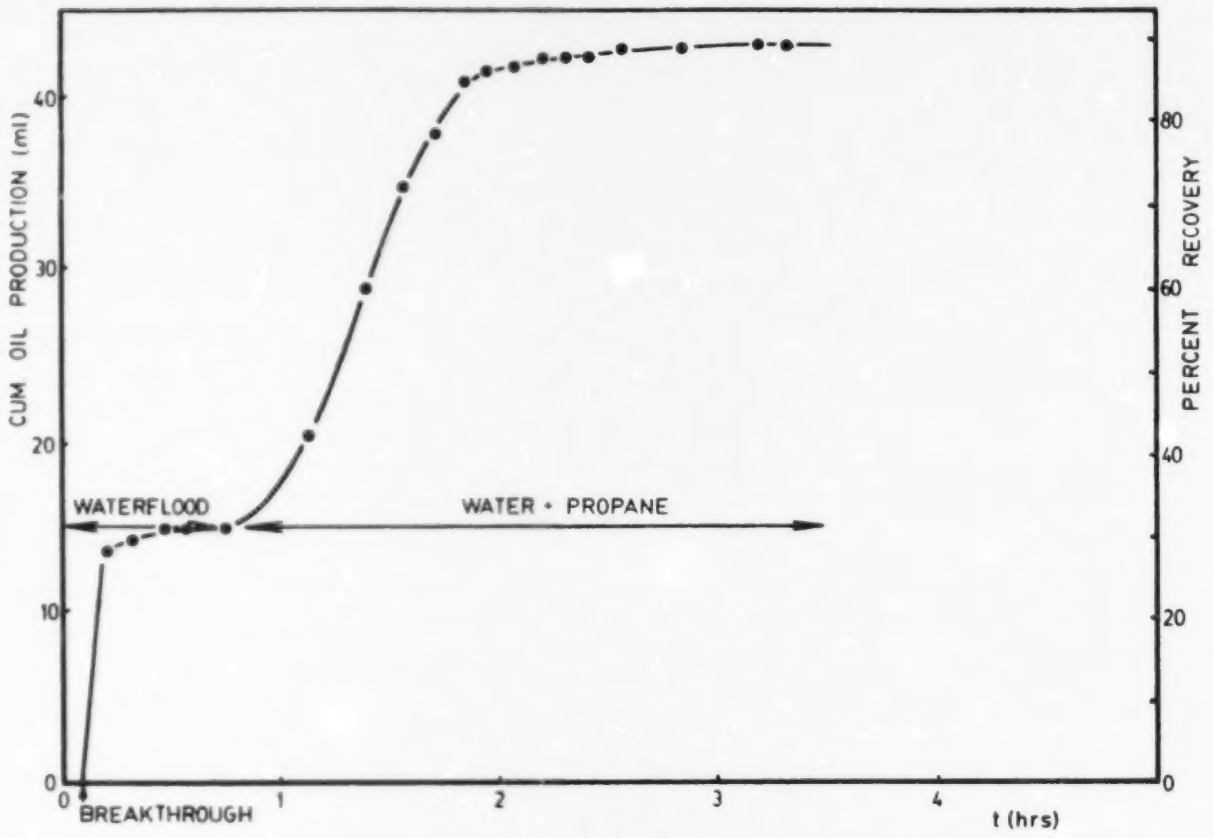

FIGURE B1a: The effect of propane injection on the cumulative oil production from hot waterflood. The average cell temperature was about 32°C at propane pressure of 145 psi. Two pump injection; oil was determined visually from centrifuged samples.

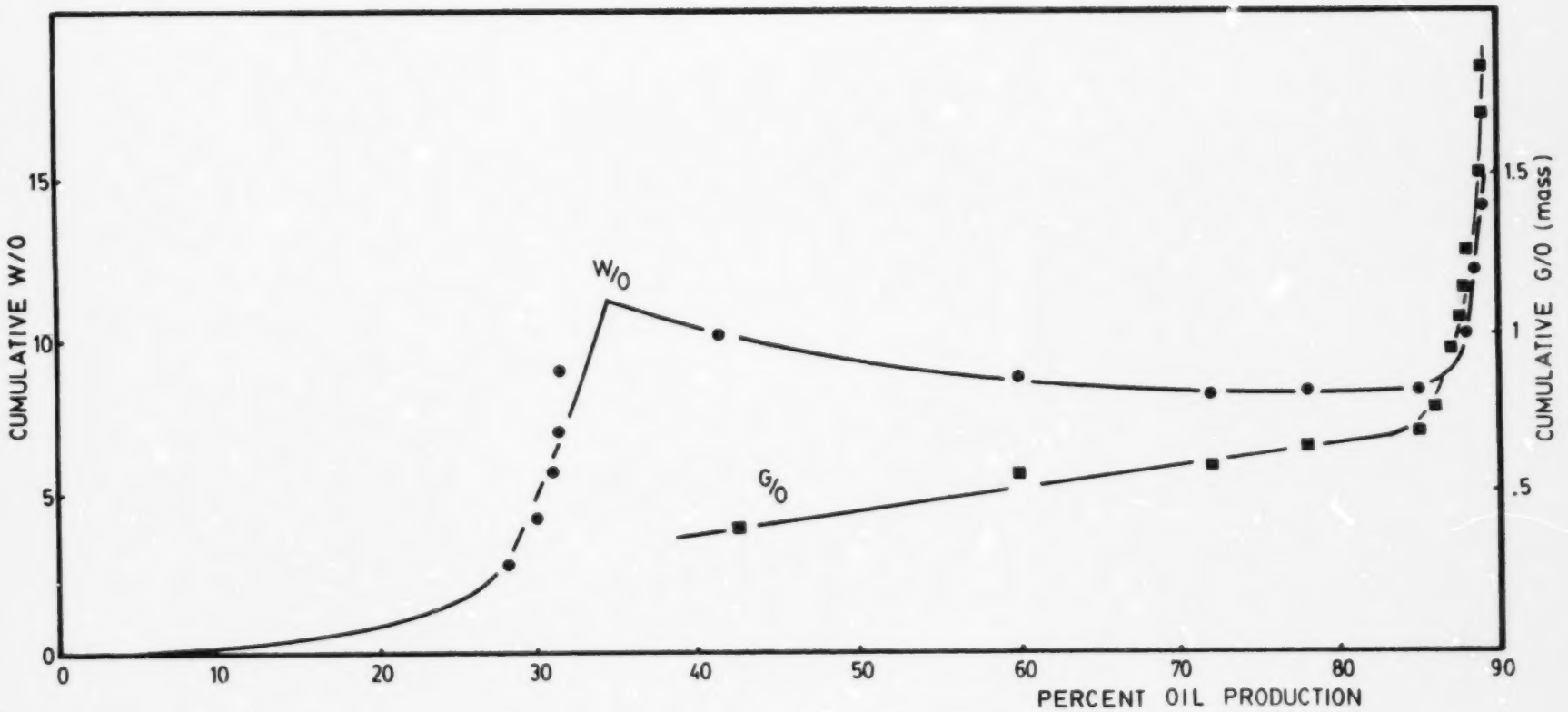

FIGURE B1b: Cumulative water/oil and propane/oil ratios as a function of oil production for the run in Fig. B1a.

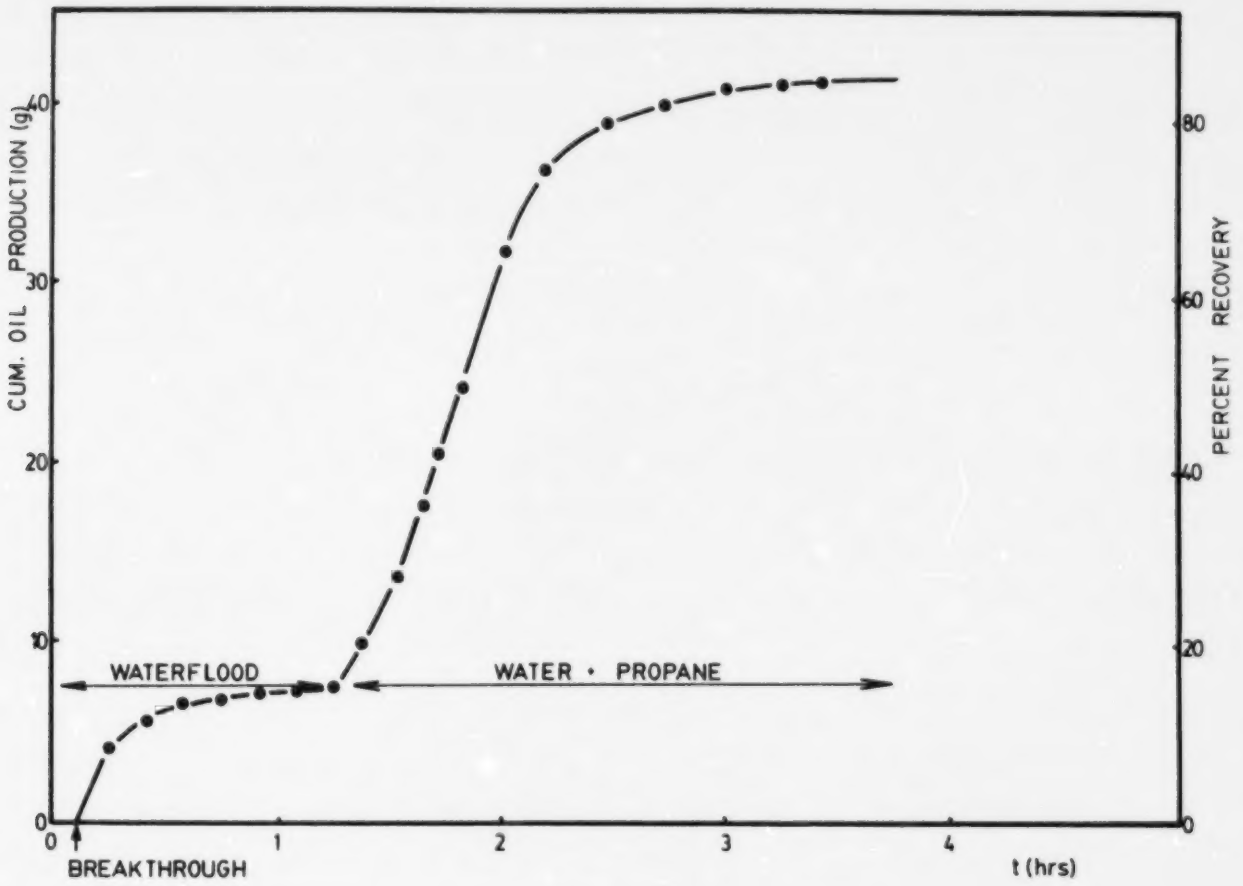

FIGURE B2a: The effect of propane injection on the cumulative oil production from hot waterflood. The average cell temperature was about 34°C at propane pressure of 150 psi. Two pump injection; oil was determined visually from centrifuged samples.

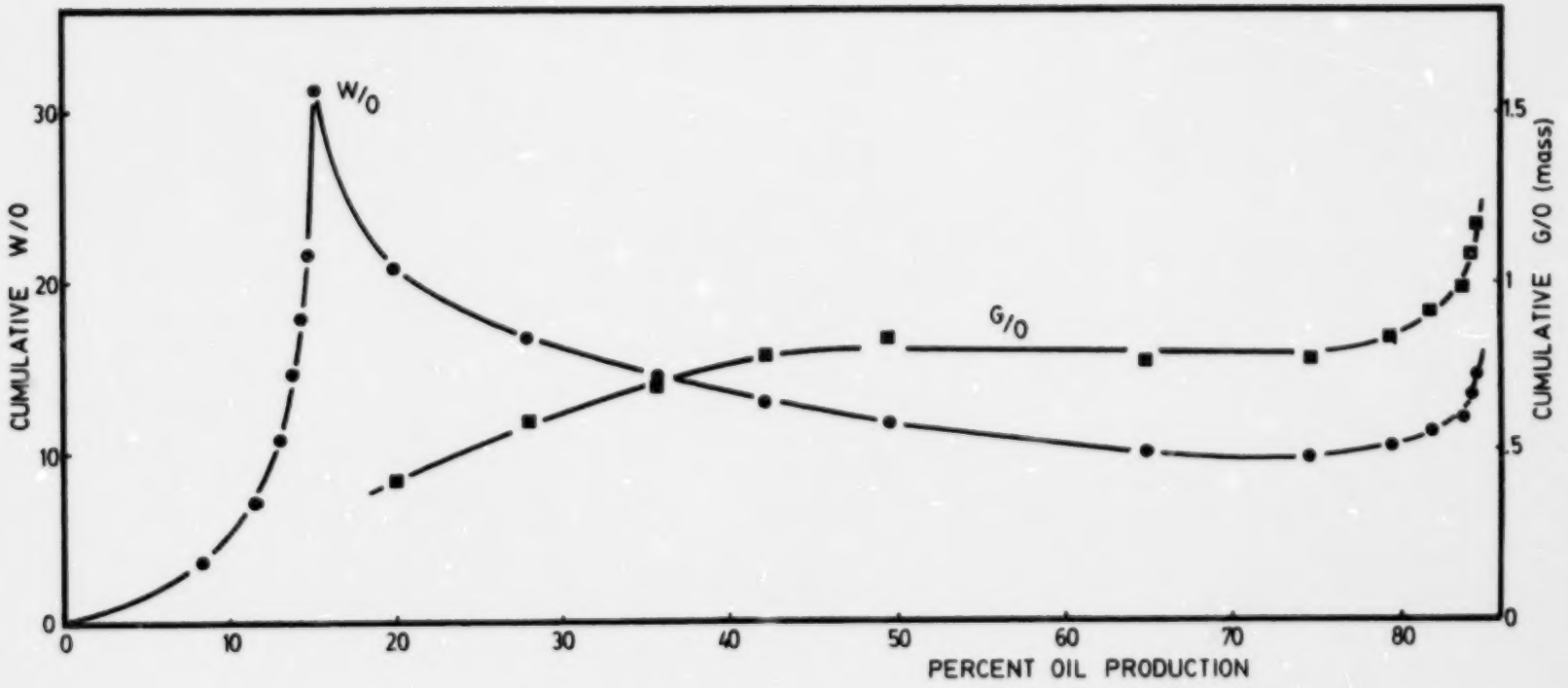

FIGURE B2b: Cumulative water/oil and propane/oil ratios as a function of oil production for the run in Fig. B2a.

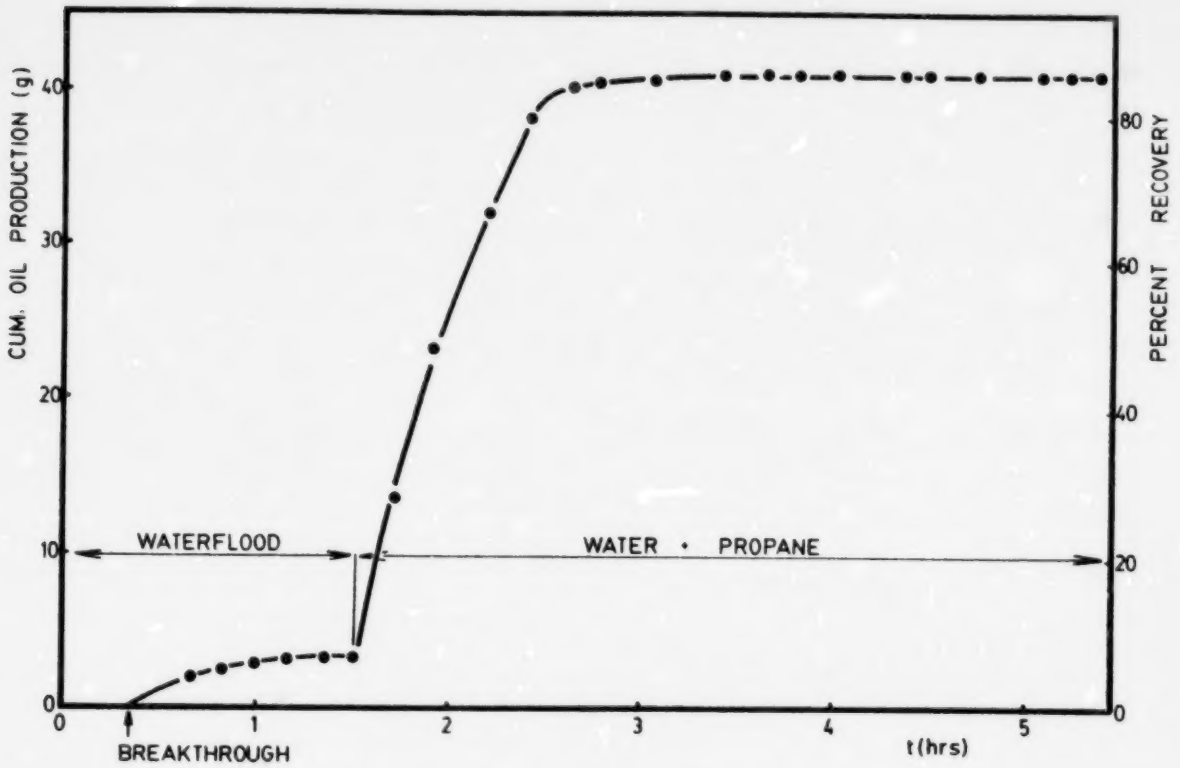

FIGURE B3a: The effect of propane injection on the cumulative oil production from hot waterflood. The average cell temperature was about 36°C at propane pressure of 150 psi. Two pump injection; oil was determined visually from centrifuged samples.

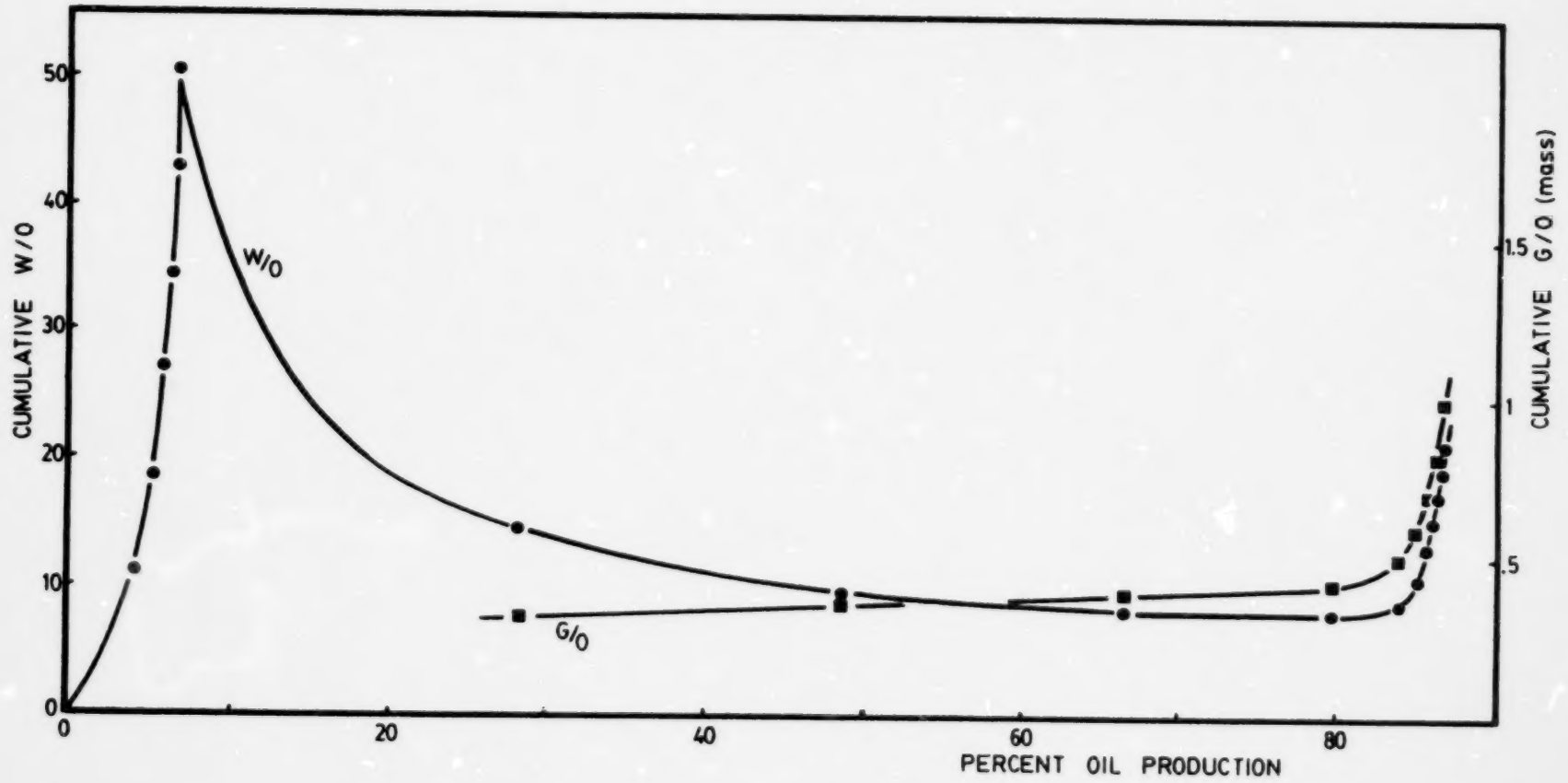

FIGURE B3b: Cumulative water/oil and propane/oil ratios as a function of oil production for the run in Fig. B3a.

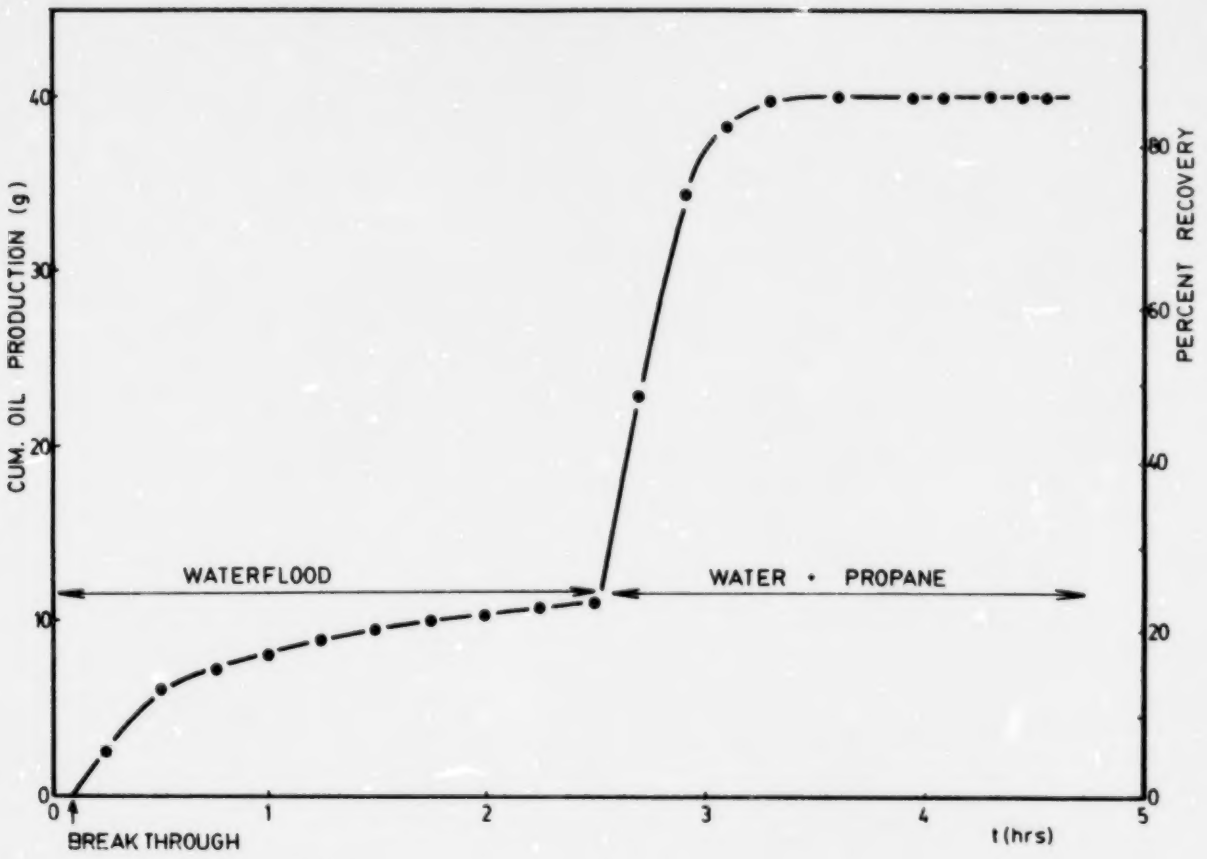

FIGURE B4a: The effect of propane injection on the cumulative oil production from hot waterflood. The average cell temperature was about 47°C at propane pressure of 210 psi. Two pump injection; oil was determined visually from centrifuged samples.

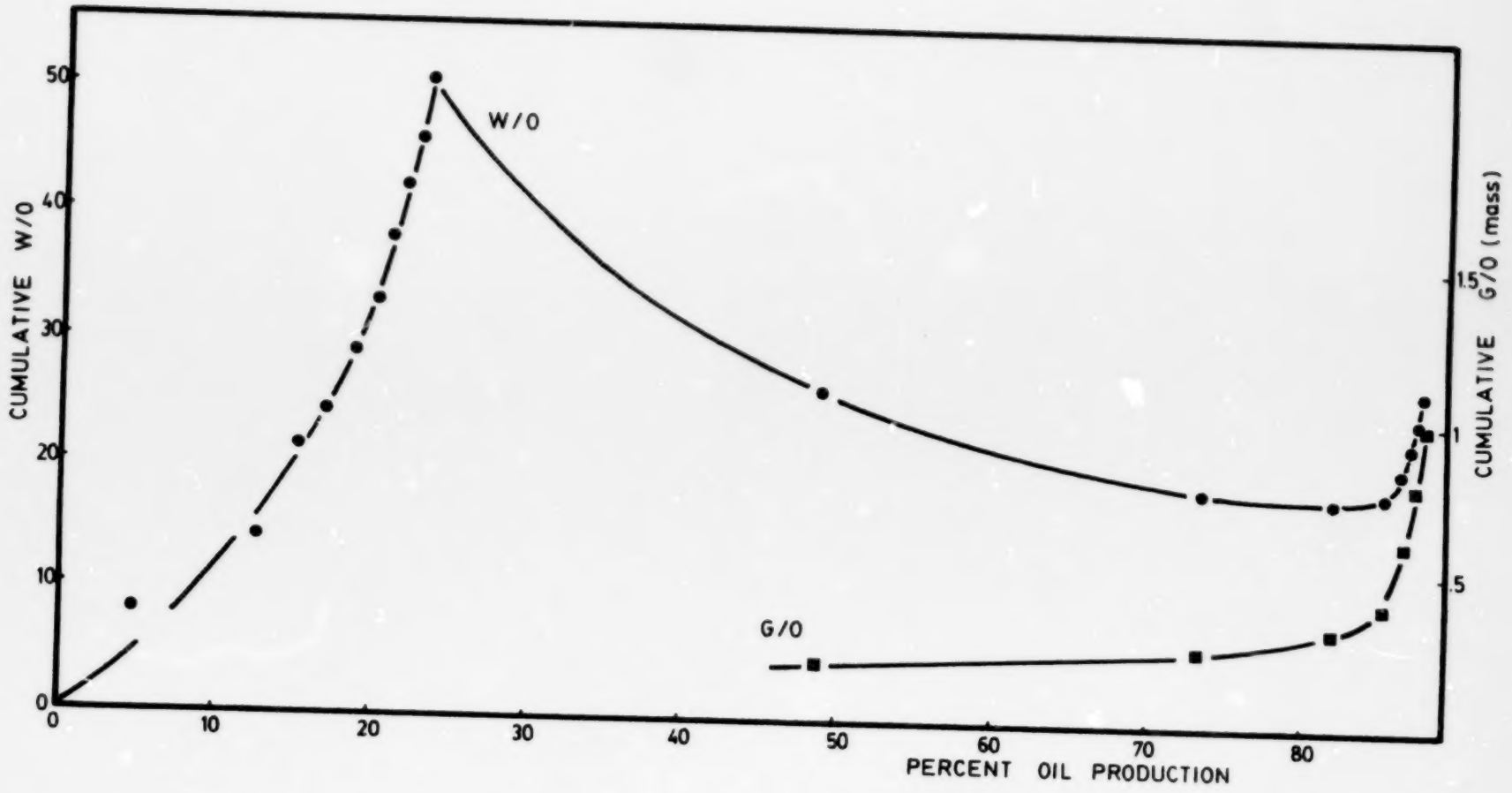

FIGURE B4b: Cumulative water/oil and propane/oil ratios as a function of oil production for the run in Fig. B4a.

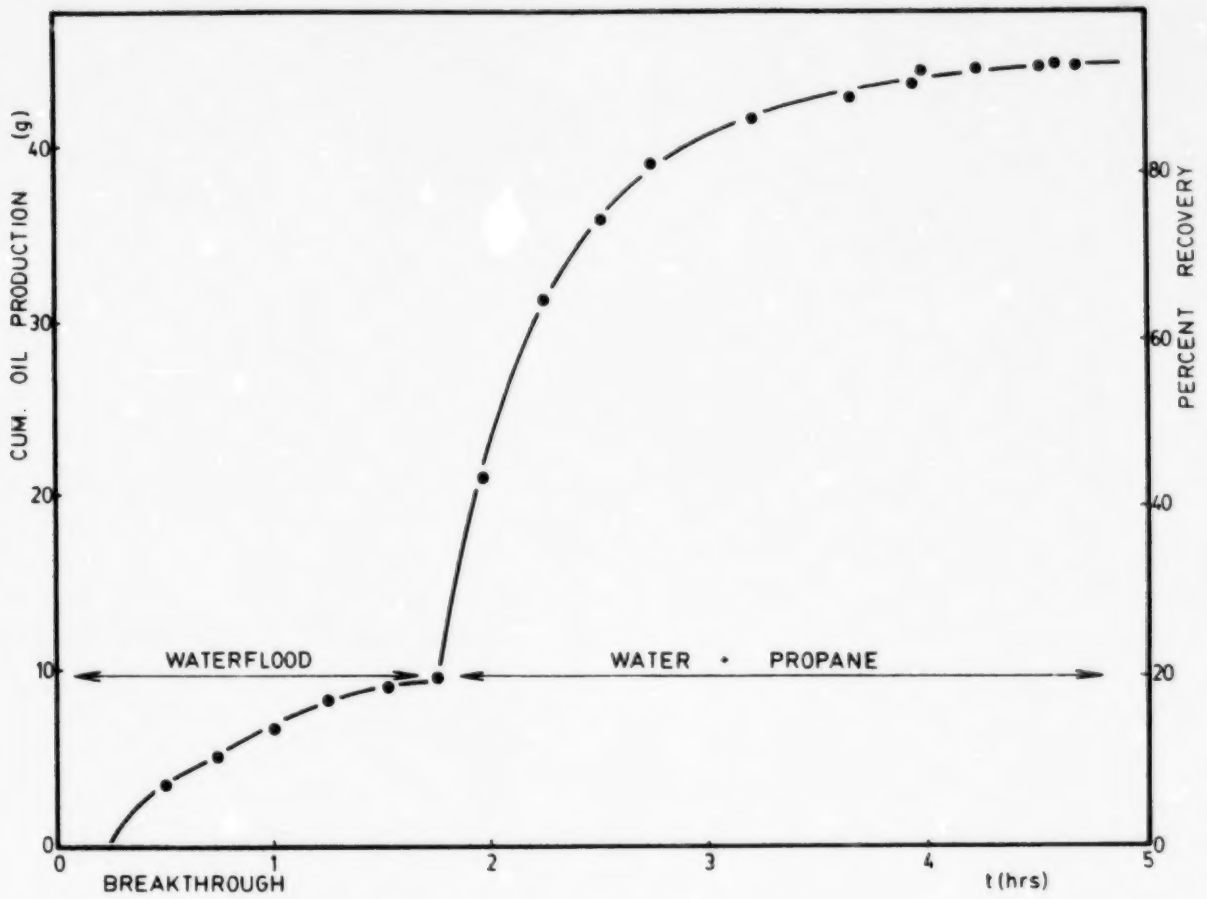

FIGURE B5a: The effect of propane injection on the cumulative oil production from hot waterflood. The average cell temperature was about 43°C at propane pressure of 210 psi. Two pump injection; oil was determined visually from centrifuged samples.

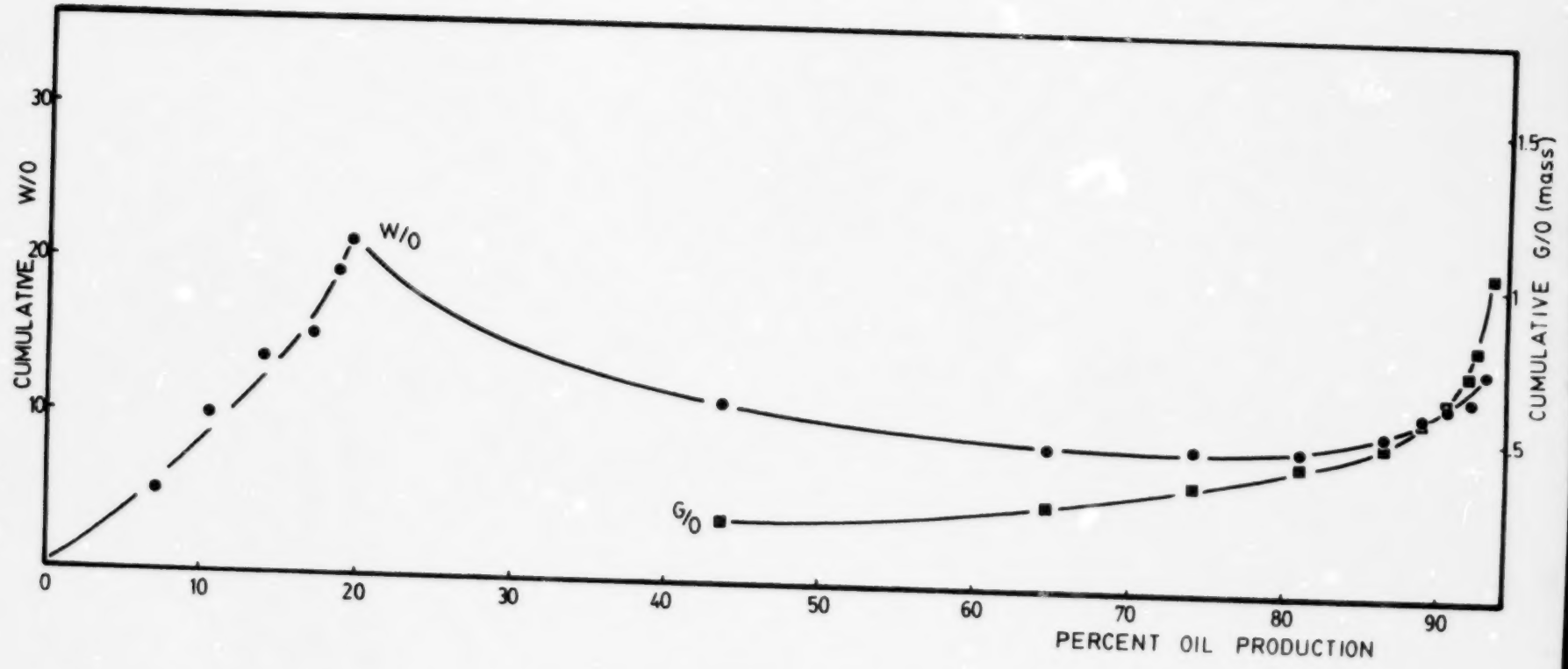

FIGURE B5b: Cumulative water/oil and propane/oil ratios as a function of oil production for the run in Fig. B5a.

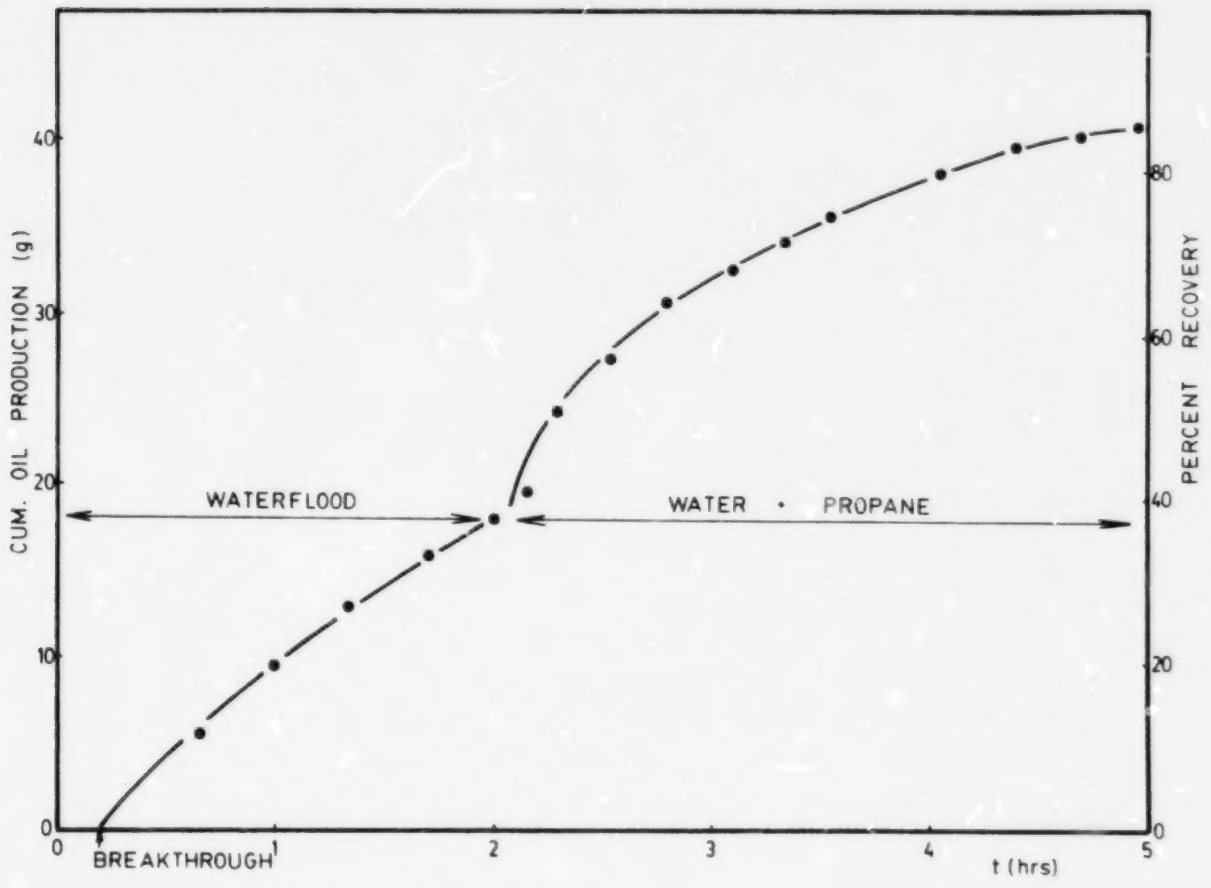

FIGURE B6a: The effect of propane injection on the cumulative oil production from hot waterflood. The average cell temperature was about 67°C at propane pressure of 350 psi. Two pump injection; oil was determined visually from centrifuged samples.

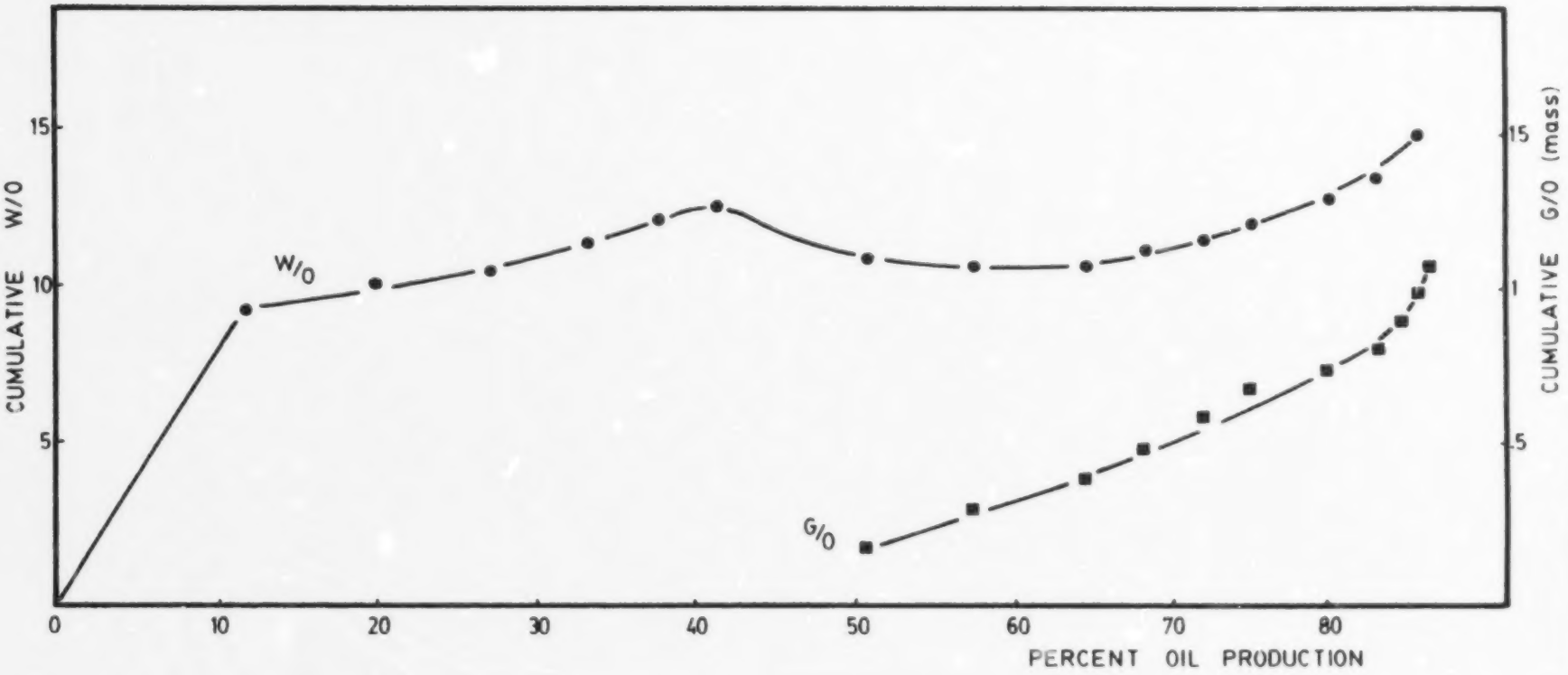

FIGURE B6b: **Cumulative water/oil and propane/oil ratios as a function of oil production for the run in Fig. B6a.**

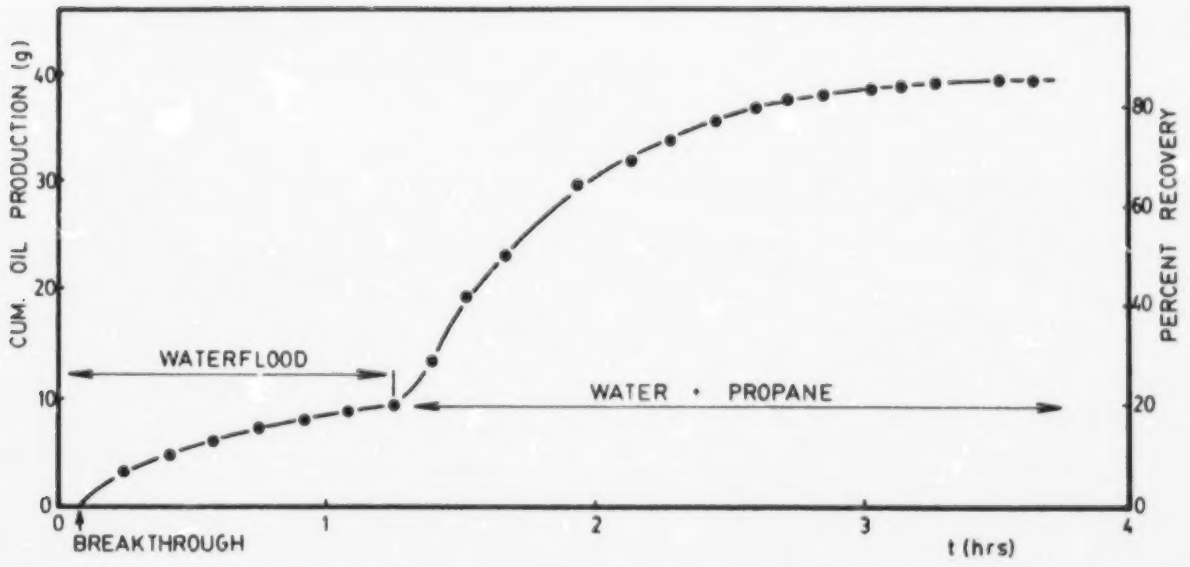

FIGURE B7a: The effect of propane injection on the cumulative oil production from hot waterflood. The average cell temperature was about 35°C at propane pressure of 150 psi. Two pump injection; oil was determined visually from centrifuged samples.

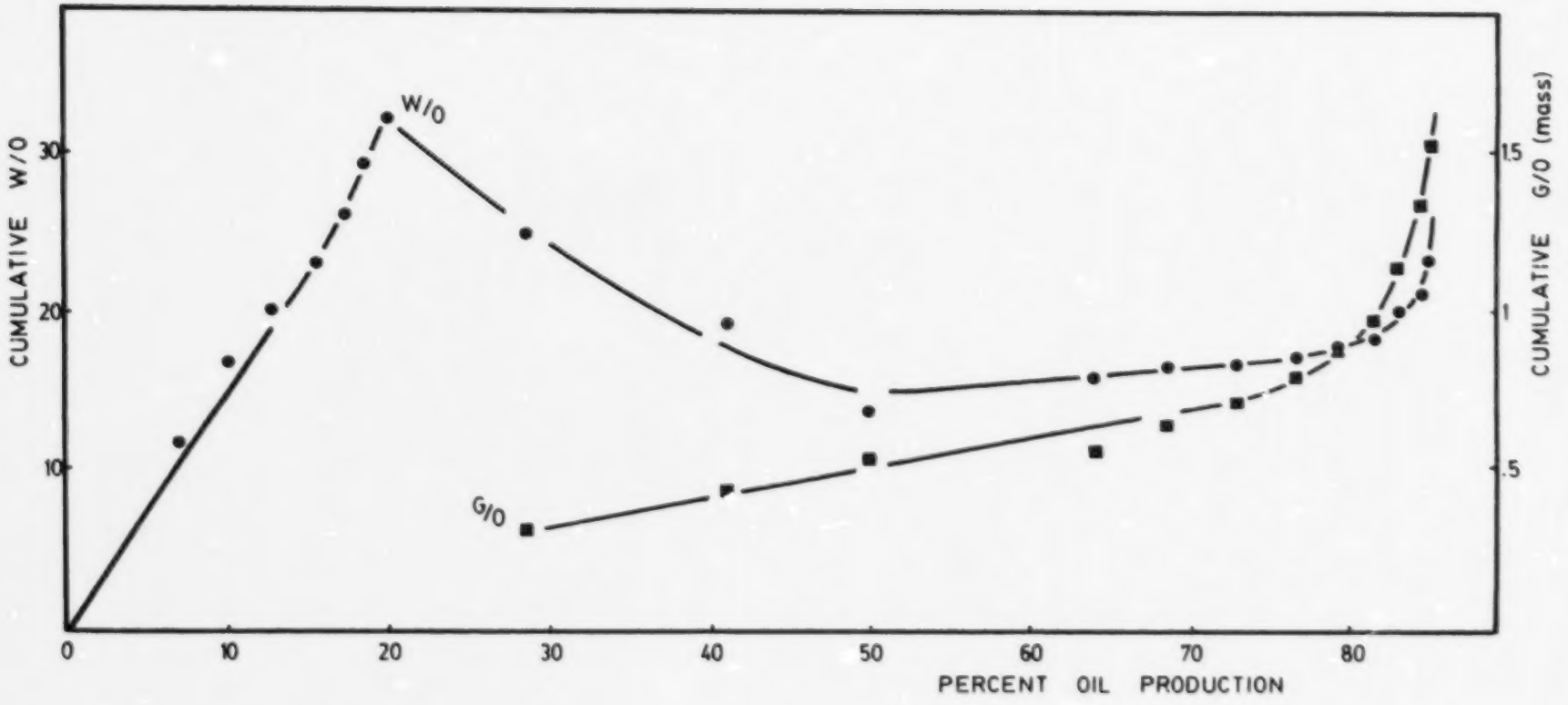

FIGURE B7b: Cumulative water/oil and propane/oil ratios as a function of oil production for the run in Fig. B7a.

APPENDIX C

PACKED CELL EXPERIMENTS WITH IMPROVED MATERIAL BALANCES

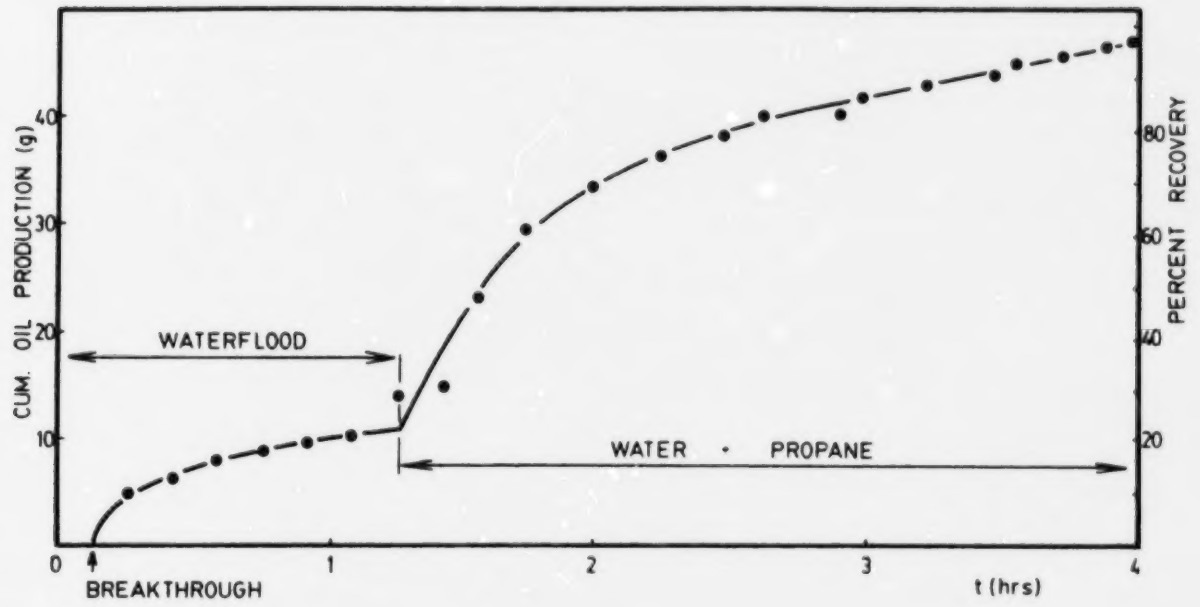

FIGURE C1a: The effect of propane injection on the cumulative oil production from hot waterflood. The average cell temperature was about 36°C at propane pressure of 150 psi. Two pump injection; water was determined by Karl-Fischer analysis.

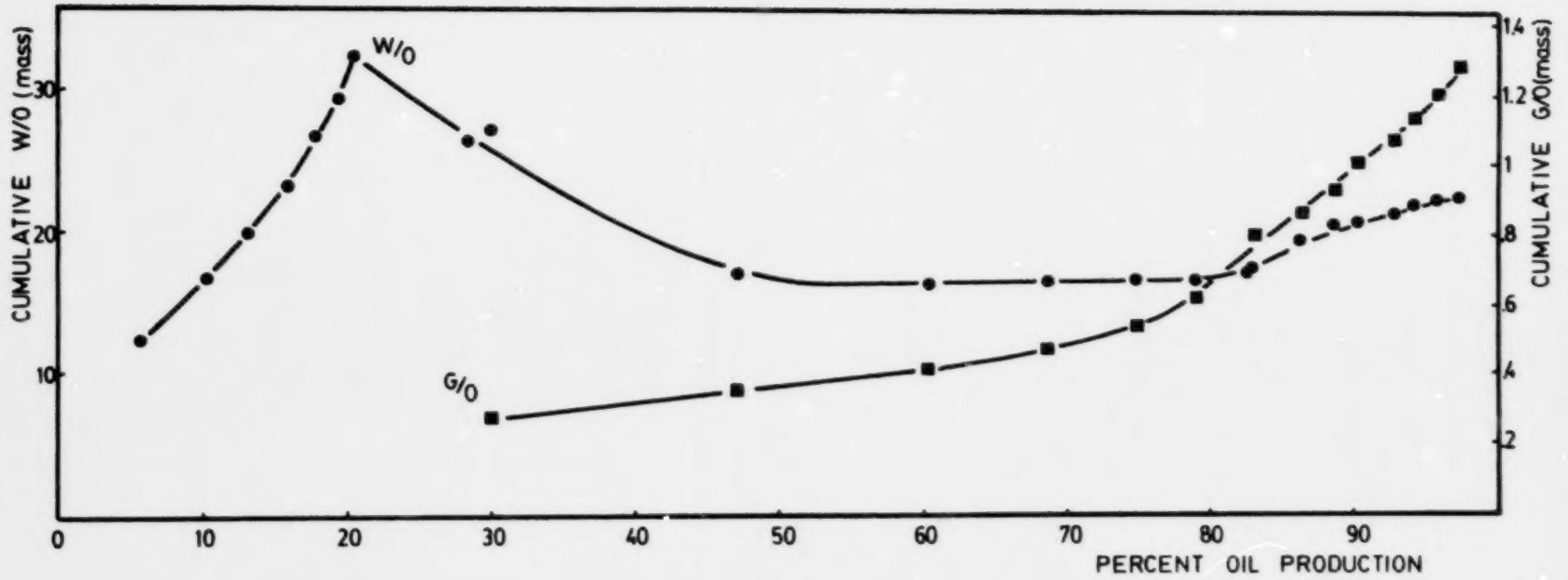

FIGURE C1b: **Cumulative water/oil and propane/oil ratios as a function of oil production for the run in Fig. C1a.**

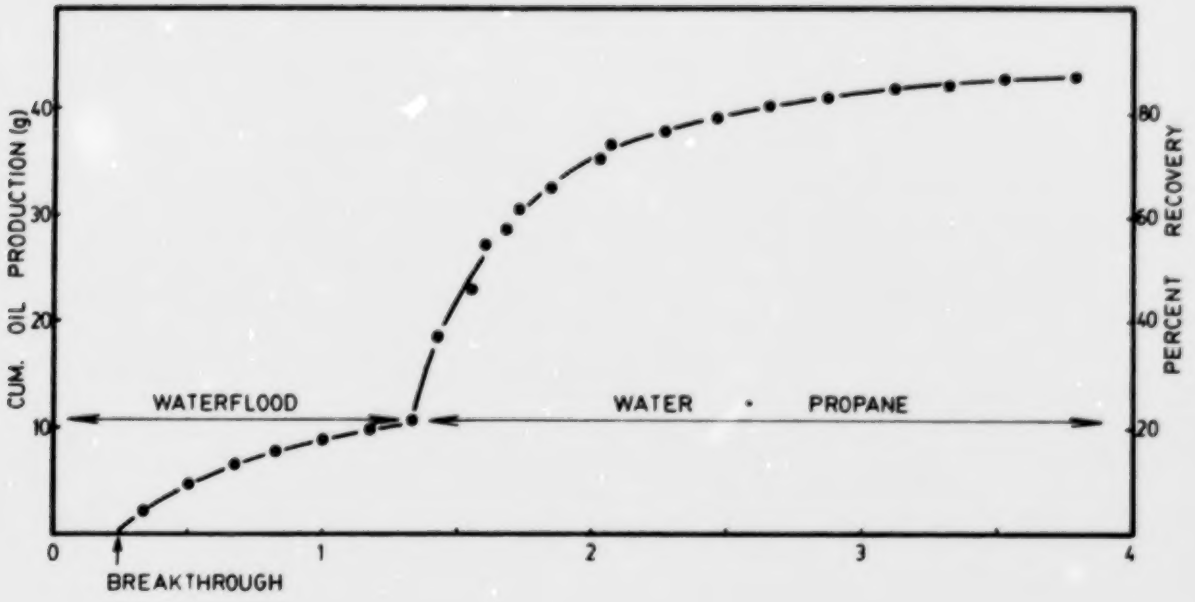

FIGURE C2a: The effect of propane injection on the cumulative oil production from hot waterflood. The average cell temperature was about 33°C at propane pressure of 300 psi. Two pump injection; water was determined by Karl-Fischer analysis.

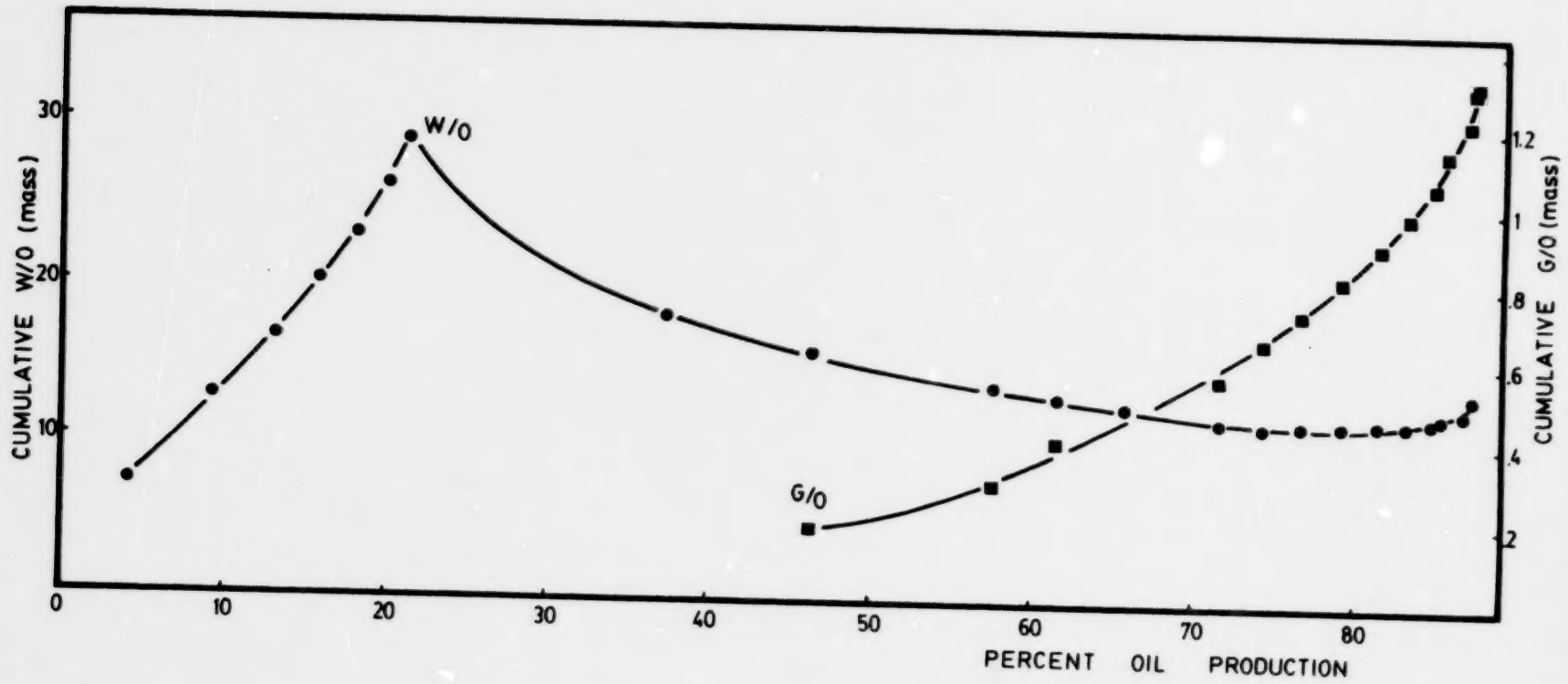

FIGURE C2b: Cumulative water/oil and propane/oil ratios as a function of oil production for the run in Fig. C2a.

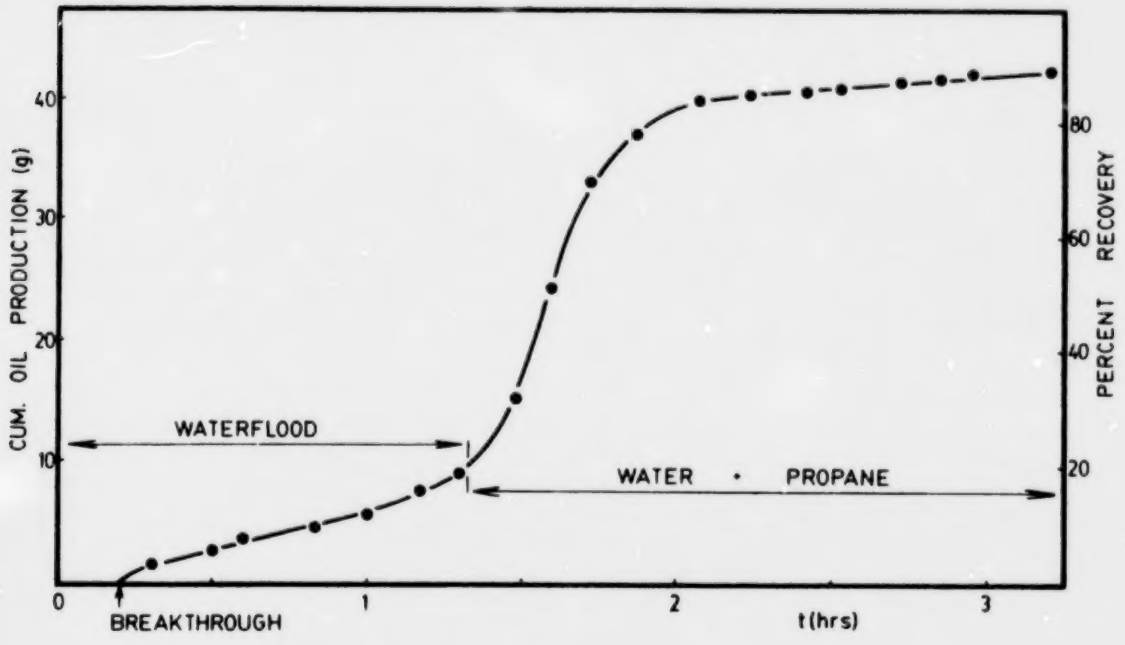

FIGURE C3a: The effect of propane injection on the cumulative oil production from hot waterflood. The average cell temperature was about 45°C at propane pressure of 180 psi. Two pump injection; water was determined by Karl-Fischer analysis.

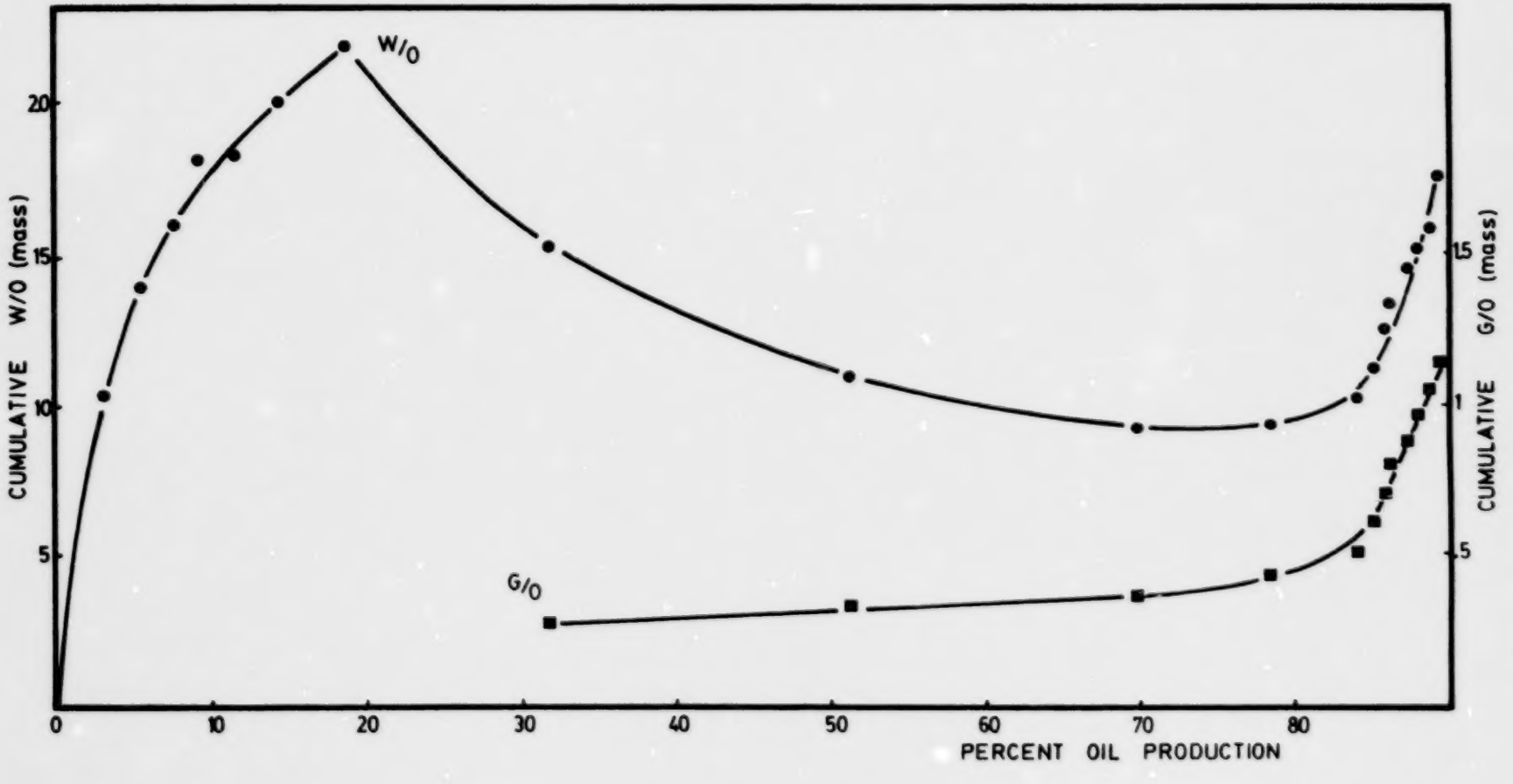

FIGURE C3b: **Cumulative water/oil and propane/oil ratios as a function of oil production for the run in Fig. C3a.**

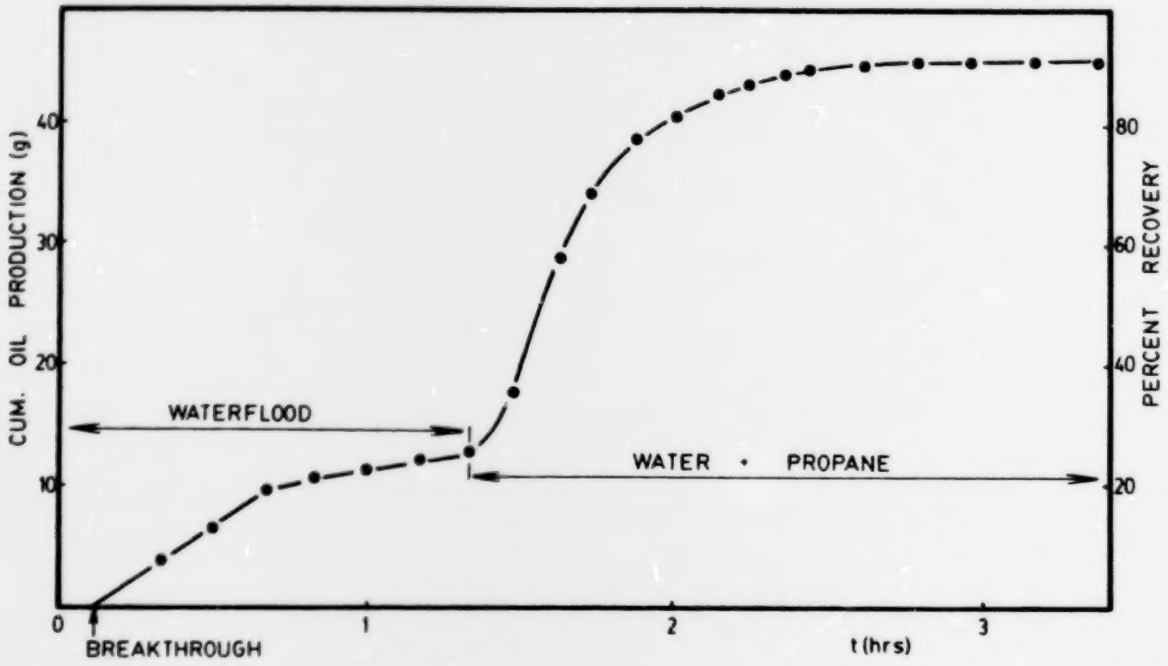

FIGURE C4a: The effect of propane injection on the cumulative oil production from hot waterflood. The average cell temperature was about 47°C at propane pressure of 200 psi. Two pump injection; water was determined by Karl-Fischer analysis.

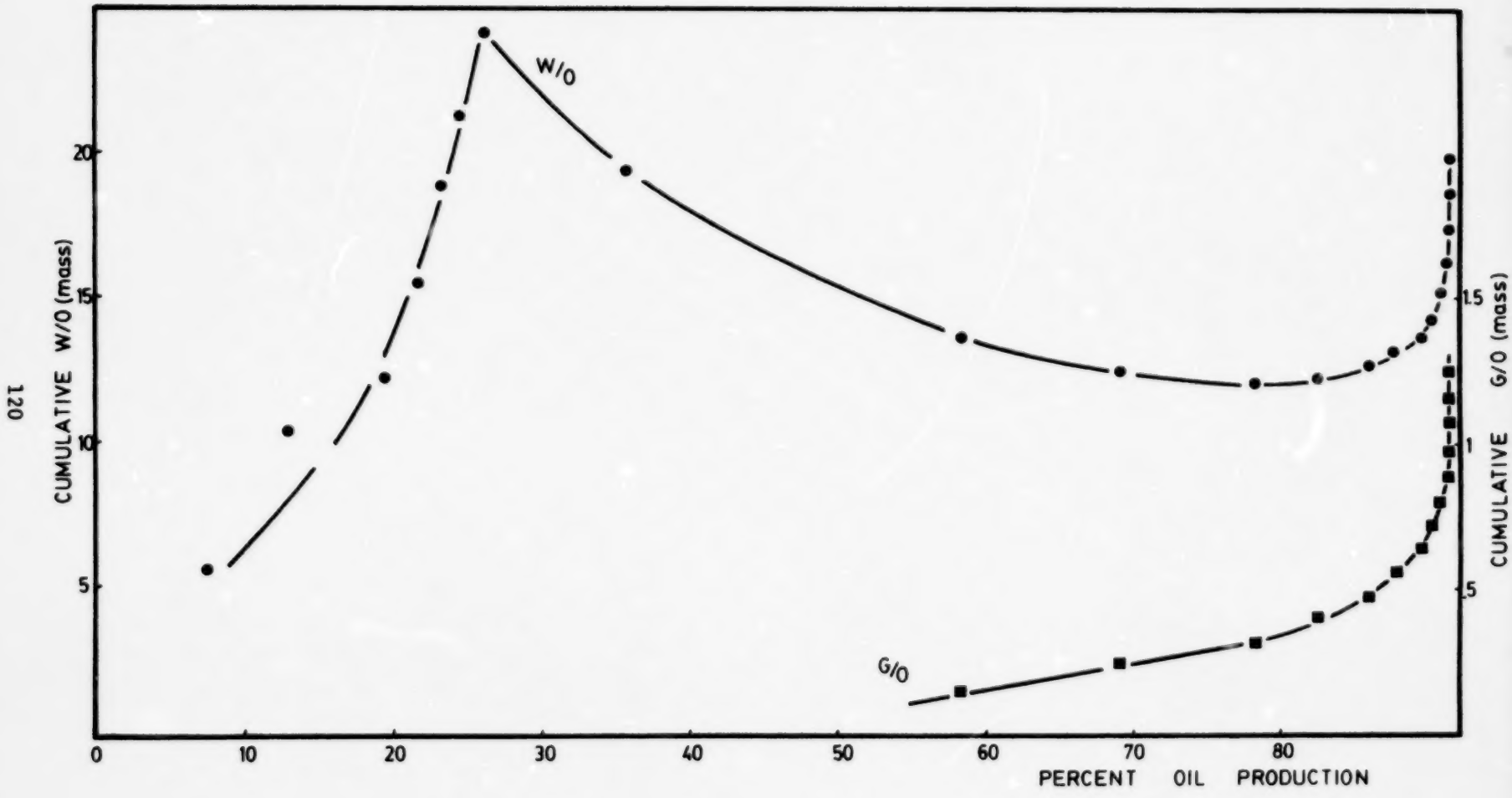

FIGURE C4b: **Cumulative water/oil and propane/oil ratios as a function of oil production for the run in Fig. C4a.**

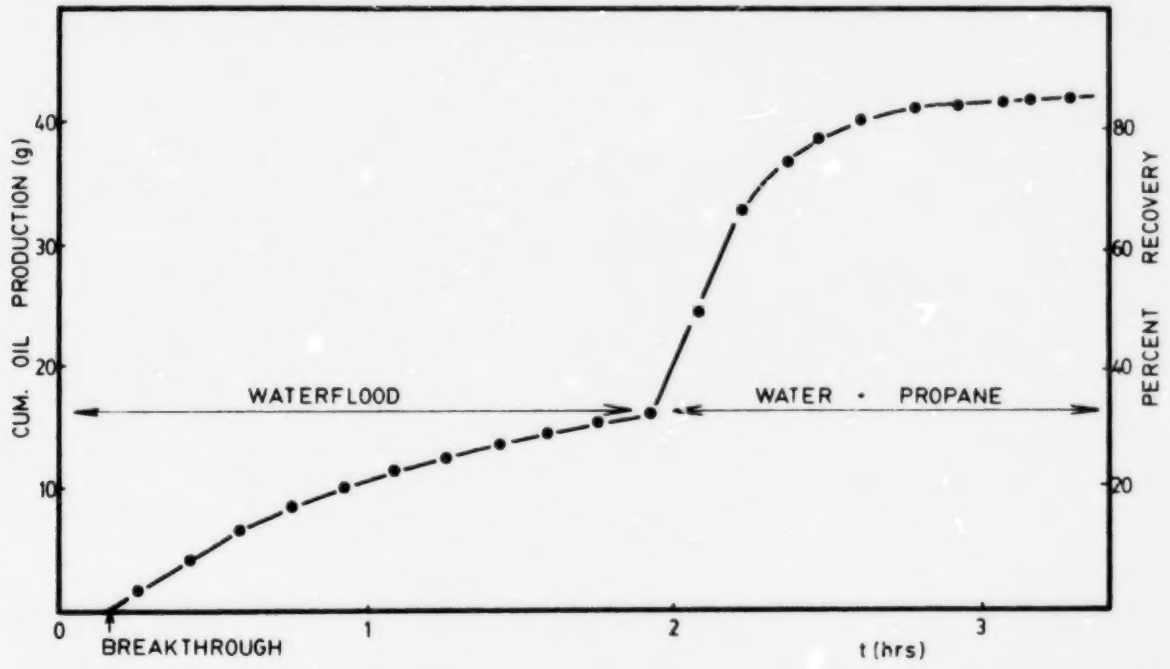

FIGURE C5a: The effect of propane injection on the cumulative oil production from hot waterflood. The average cell temperature was about 55°C at propane pressure of 250 psi. Two pump injection; water was determined by Karl-Fischer analysis.

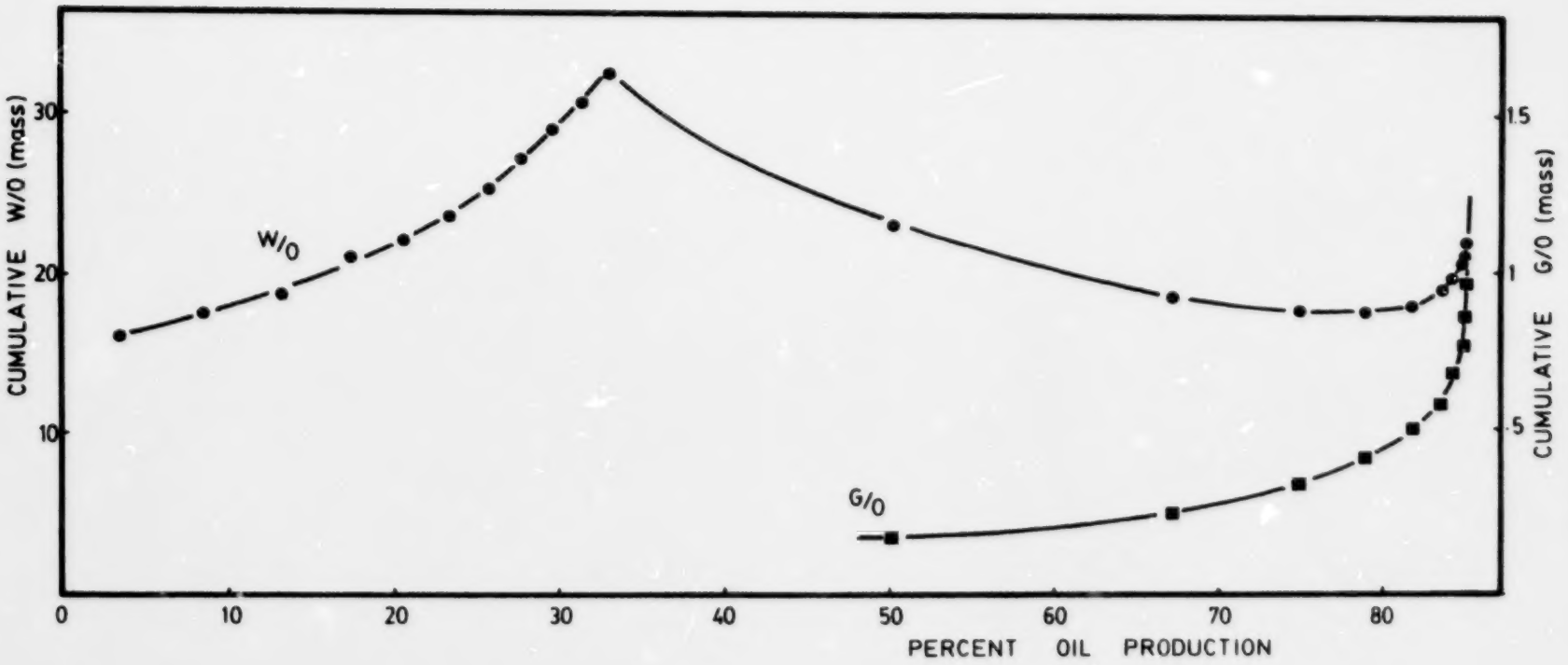

FIGURE C5b: **Cumulative water/oil and propane/oil ratios as a function of oil production for the run in Fig. C5a.**

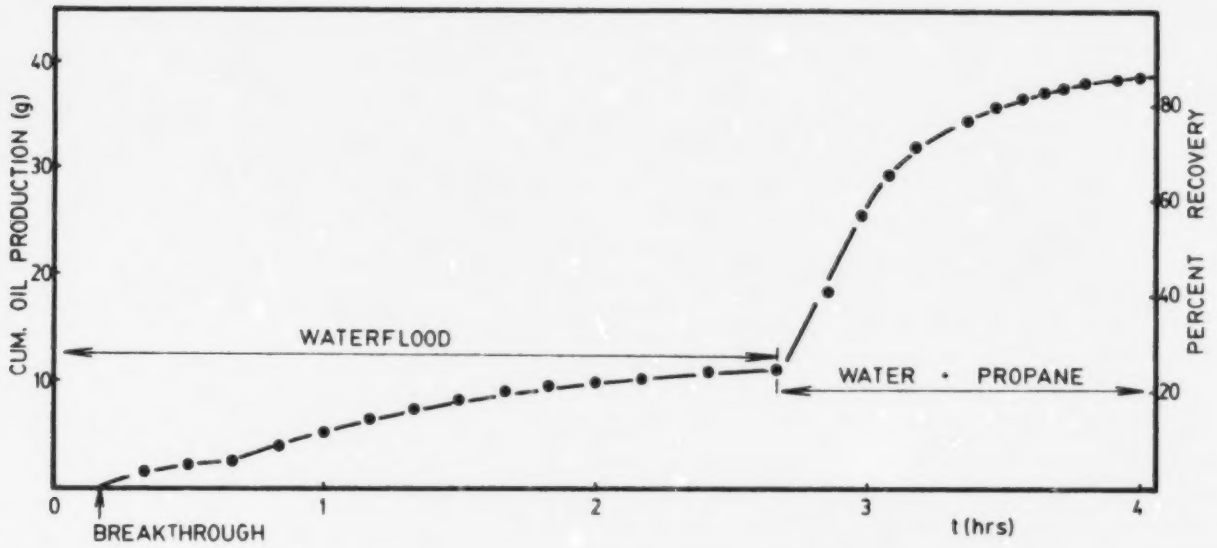

FIGURE C6a: The effect of propane injection on the cumulative oil production from hot waterflood. The average cell temperature was about 44°C at propane pressure of 200 psi. Two pump injection; water was determined by Karl-Fischer analysis.

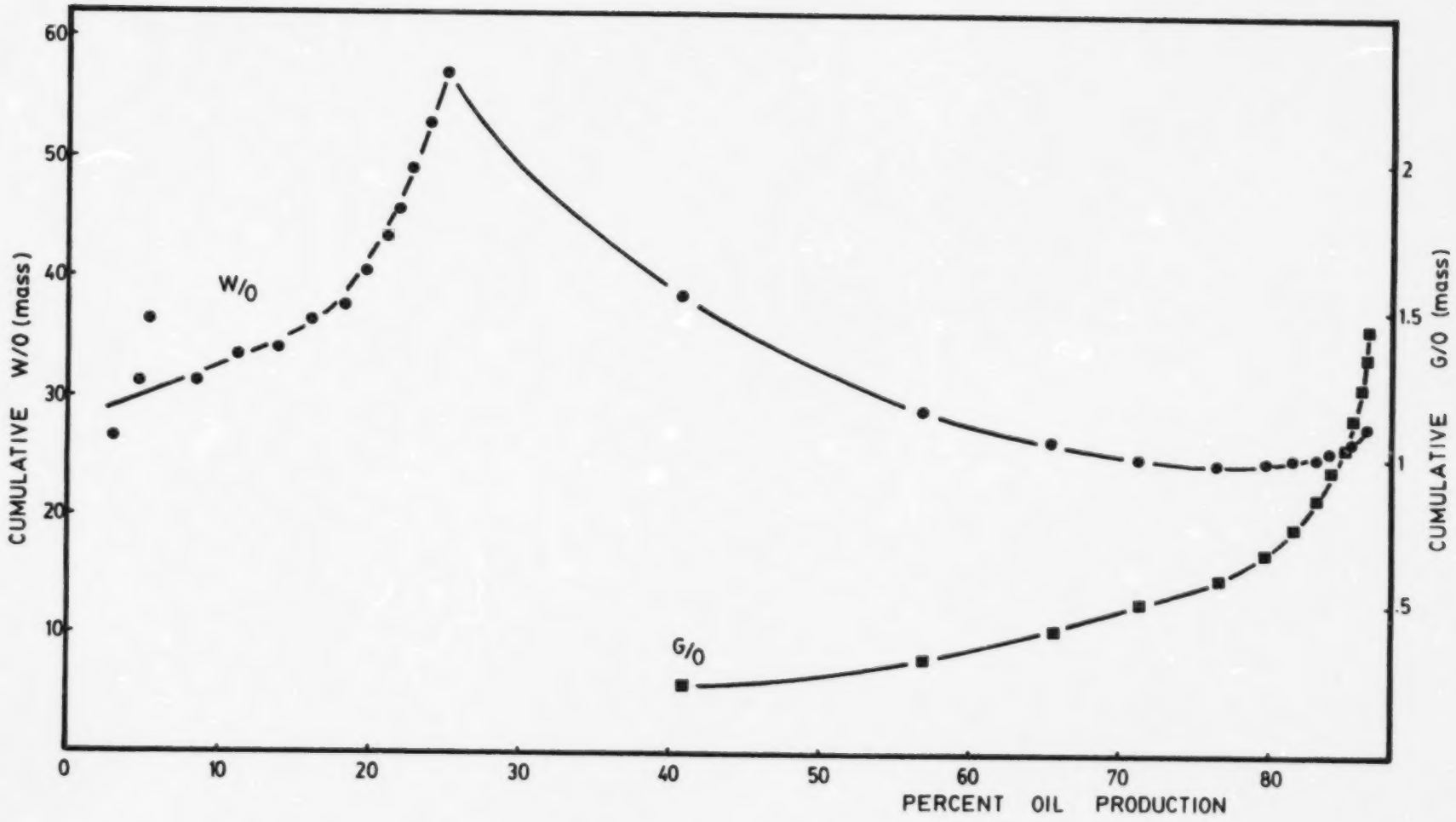

FIGURE C6b: Cumulative water/oil and propane/oil ratios as a function of oil production for the run in Fig. C6a.